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COUNTEREVASION STUDIES

SEMI-ANNUAL TECHNICAL REPORT NO. 6 - PART B
1 NOVEMBER 1975 TO 31 MAY 1976

Prepared by
David Sun

TEXAS INSTRUMENTS INCORPORATED
Equipment Group
Post Office Box 6015
Dallas, Texas 75222

Contract No. F44620-73-C-0055
Amount of Contract: $294,749
Beginning 23 April 1973
Ending 30 June 1976

Prepared for

AIR FORCE OFFICE OF SCIENTIFIC RESEARCH

Sponsored by

ADVANCED RESEARCH PROJECTS AGENCY
Nuclear Monitoring Research Office
ARPA Program Code No. F10
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31 May 1976

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Fifteen earthquakes with known PDE (Preliminary Determination of Epicenters) depths have been analyzed using teleseismic short-period P-waves recorded at NORSAR. Results from this analysis indicate that mis-decomposition by cepstrum analysis is unlikely, especially if the analyst follows the appropriate criteria closely. → next page

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Also, two presumed underground explosions from eastern Kazakh (EKZ) have been analyzed using teleseismic short-period P-waves recorded at nine NORSAR subarrays with signal-to-noise ratio above 18 dB. Waveforms recorded at nine subarrays are quite dissimilar, especially for two subarrays on the west side of NORSAR. However, cepstrum-analyzed results are fairly consistent among them. The difference in the resolved delay times is one sampling unit (0.1 second) maximum. Although these subarrays are not located widely apart enough to be considered as separate stations at different azimuths, the good agreement of cepstrum-analyzed results among them is definitely a plus toward better recognition of the capability of the cepstrum analysis.

Finally, beamforming in cepstrum time domain (BFCEP) to enhance the detection of the cepstral peaks due to the multipath operator has been formulated and implemented. Several sets of synthetic signals, which simulate various cases of interest, have been used in the experiments. Preliminary results show that BFCEP in general does achieve its original purpose. Moreover, it appears that BFCEP can be expected to produce a better effect when signals used in BFCEP are less correlated. This, in the real world, may imply that BFCEP will work more effectively with the world-wide network data than with the single array data.

ABSTRACT

Fifteen earthquakes with known PDE (Preliminary Determination of Epicenters) depths have been analyzed using teleseismic short period P-waves recorded at NORSAR. Results from this analysis indicate that misdecomposition by cepstrum analysis is unlikely, especially if the analyst follows the appropriate criteria closely.

Also, two presumed underground explosions from eastern Kazakh (EKZ) have been analyzed using teleseismic short period P-waves recorded at nine NORSAR subarrays with signal-to-noise ratio above 18 dB. Waveforms recorded at nine subarrays are quite dissimilar, especially for two subarrays on the west side of NORSAR. However, cepstrum-analyzed results are fairly consistent among them. The difference in the resolved delay times is one sampling unit (0.1 second) maximum. Although these subarrays are not located widely apart enough to be considered as separate stations at different azimuths, the good agreement of cepstrum-analyzed results among them is definitely a plus toward better recognition of the capability of the cepstrum analysis.

Finally, beamforming in cepstrum time domain (BFCEP) to enhance the detection of the cepstral peaks due to the multipath operator has been formulated and implemented. Several sets of synthetic signals, which simulate various cases of interest, have been used in the experiments. Preliminary results show that BFCEP in general does achieve its original purpose. Moreover, it appears that BFCEP can be expected to produce a better effect when signals used in BFCEP are less correlated. This, in the real world, may imply that BFCEP will work more effectively with the worldwide network data than with the single array data.

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SECTION 1
INTRODUCTION

During this report period, the complex cepstrum technique has been further evaluated and validated by undertaking the following two tasks:

- Analysis of fifteen earthquakes from known PDE (Preliminary Determination of Epicenters) depths.
- Analysis of two presumed underground explosions from eastern Kazakh (EKZ) using all available NORSAR subarray beam traces.

Work accomplished for these two tasks is presented in Sections II and III. Also, a technique called "beamforming in the cepstrum time domain" has been investigated as a possible means of improving the complex cepstrum technique or of detecting cepstral peaks due to the multipath operator. Results are discussed in Section IV.

SECTION II

CEPSTRUM ANALYSIS OF EARTHQUAKES

A. INTRODUCTION

In our previous reports (Lane and Sun, 1974a, 1974b, 1975; Sun, 1975), cepstrum analysis was applied quite successfully to both synthetic and real signals. For synthetic signals, there is no question in judging the successfulness of the cepstrum analysis, since the criteria can be made very objective. For real signals, however, due to the inherent nature of the problem, the interpretation of the cepstrum analyzed results are more dependent on the individual analyst's experiences and opinions. Nevertheless, the successful decompositions of a large number of real mixed signals by cepstrum analysis have been well demonstrated (Lane and Sun, 1975; Sun, 1975). Therefore, the capability of the cepstrum analysis in decomposing a mixed signal is not the one in question. Rather, the problem of interest is to ascertain whether the cepstrum analysis will give any arbitrary decomposition even when no multiple arrivals in the signal are being analyzed. For this purpose, fifteen earthquakes with known PDE depths have been chosen to be studied here. These earthquakes have various estimated focal depths between 10 km and 60 km. It is known that for earthquakes the depth phase (pP) usually is observed only in the deep focus events and arrives much later than the direct P-phase. Therefore, when we analyze these earthquakes by using a signal length of 3 to 5 seconds (comparable to that used in analyzing presumed underground explosions (Lane and Sun, 1975)), we are sure that there is no depth phase contained in the signal being analyzed.

B. SELECTION OF SIGNALS AND CRITERIA OF SUCCESSFUL CEPSTRUM ANALYSIS

1. Signals

Signals which will be cepstrum-analyzed in this section are teleseismic short period P-waves of fifteen earthquakes recorded at NORSAR. Table II-1 presents the source information for these events.

One difficult point in applying the cepstrum analysis to earthquakes is the selection of their signal lengths. Unlike previously analyzed P-waves of presumed underground explosions which usually have well defined signal length, the P-waves of these earthquakes are more complicated and their signal durations are much longer. Figure II-1 shows the typical short period P-waves of presumed underground explosions and earthquakes recorded at NORSAR subarray. Since our purpose here is to ascertain whether the cepstrum analysis will give any arbitrary decomposition even when there is no depth phase in the signal being analyzed, the selection of signal length is made to ensure that the pP-phase is excluded. Also, for the convenience of cepstrum analysis, signal length is chosen as short as possible under the condition that waveform complexity is preserved. Signal lengths of the earthquakes so chosen are also given in Table II-1.

It is noticed that nine events have PDE estimated focal depths around 50 km and distances to NORSAR greater than 40 degrees. For these events, pP-phases should arrive at NORSAR at least 12 seconds later than the corresponding direct P-phases (Richter, 1958). And for the remaining six events with shallow focal depths between 6 km and 20 km, the pP-phase should not be observed. Therefore, for all signal lengths which are chosen for events in Table II-1, we are certain that there will be no pP-phases.

TABLE II-1

EARTHQUAKES WITH KNOWN PDE DEPTHS

Event I. D.	Date	Location		m_b	h (km)	Δ^o to NORSAR	Signal Length (sec)*
		Latitude	Longitude				
KUR/099/04N	04/09/71	43.4N	147.6E	4.8	50	70.0	2.9
KAM/099/08N	04/09/71	56.3N	162.7E	4.9	45	60.8	2.6
KAM/166/14N	06/15/71	52.8N	160.8E	5.1	55	63.9	6.4
KUR/190/16N	07/10/71	43.5N	147.7E	4.9	46	69.9	3.6
KUR/213/02N	08/01/71	50.4N	156.8E	5.6	20	65.5	5.8
IRA/239/05N	08/27/71	30.2N	50.7E	5.0	54	40.3	4.8
IRA/245/18N	09/02/71	30.1N	50.8E	5.1	45	40.4	2.7
SAK/249/06N	09/06/71	46.4N	141.1E	5.6	16	65.5	4.7
SAK/249/13N	09/06/71	46.7N	141.4E	6.1	39	65.3	4.7
SAK/251/11N	09/08/71	46.4N	141.4E	5.9	6	65.5	5.5
IRA/251/12N	09/08/71	29.2N	60.0E	5.4	12	45.2	2.4
HON/251/07N	09/08/71	37.2N	141.3E	5.5	56	73.9	3.8
KUR/252/23N	09/09/71	44.4N	150.9E	6.0	7	69.8	2.7
HON/258/14N	09/15/71	39.1N	143.4E	5.8	17	72.8	4.3
IRA/278/18N	10/05/71	27.2N	55.8E	5.1	39	45.1	4.0

*Signal length chosen for cepstrum analysis

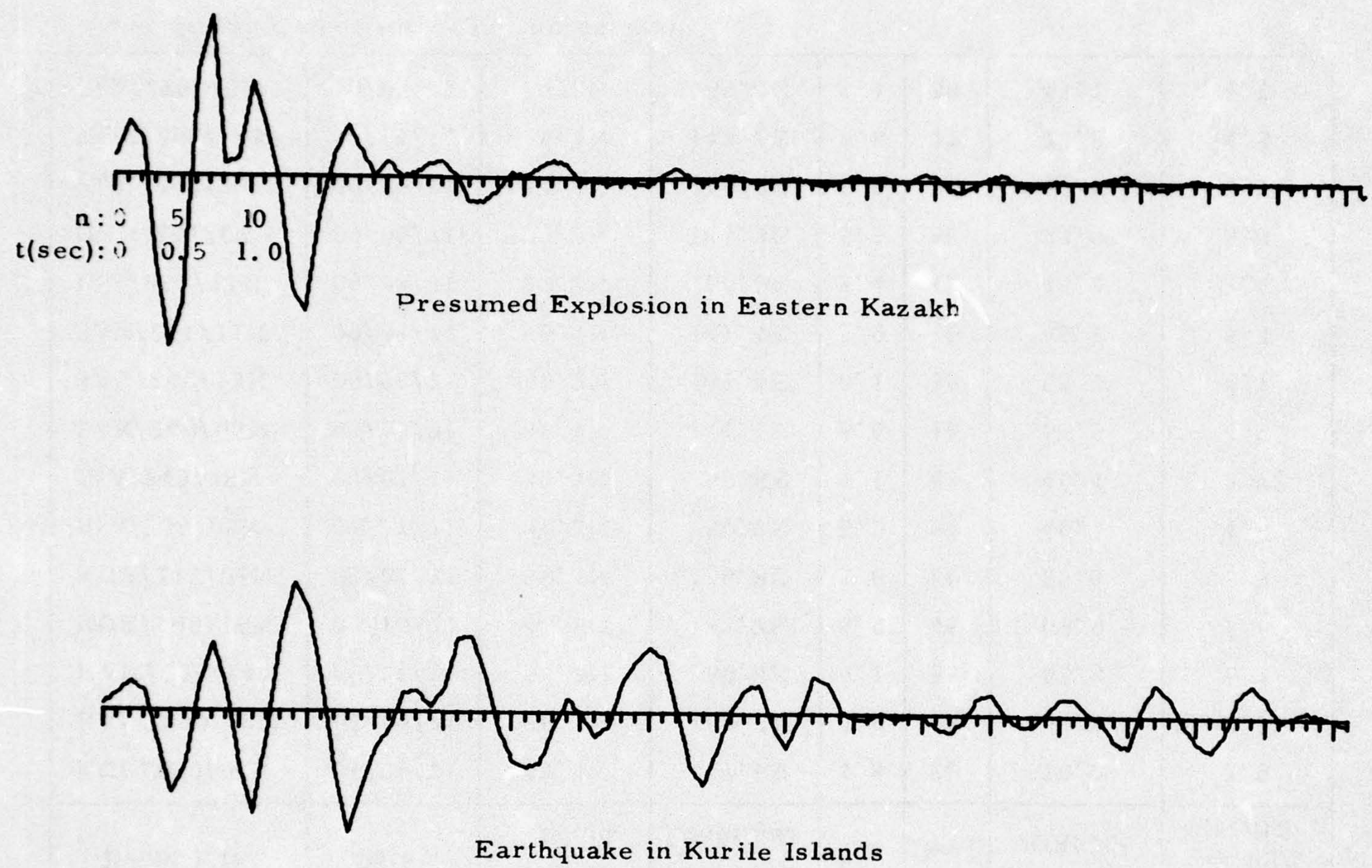


FIGURE II-1

TELESEISMIC SHORT-PERIOD P-WAVES OF PRESUMED EXPLOSION AND EARTHQUAKE RECORDED AT NORSAR

2. Criteria

Before applying the cepstrum analysis to these signals, it is desirable to set up some criteria for judging the results. To facilitate the statements of these criteria, we can group the results into two cases: first, the mixed signal consists of only two single arrivals, and second, the mixed signal consists of more than two single arrivals. As discussed in a previous report where Russian PNE events were analyzed (Lane and Sun, 1975), the number of paths of cepstrum analysis required to completely decompose a given mixed signal is equal to the number of single arrivals contained in that mixed signal minus one. Therefore, for the second case, criteria must be provided for each path of cepstrum analysis applied and also for the final cepstrum decomposition obtained. In the following paragraphs, two sets of criteria will be given for these two cases.

For the first case, let us assume that the mixed signal x(n) is cepstrum-decomposed into two single arrivals as follows:

$$x(n) = \underset{\sim}{s}_1(n) + \underset{\sim}{s}_2(n - \underset{\sim}{n}_o) \qquad n \leq N, \qquad \text{(II-1)}$$

where N is the signal length of x(n).

A real mixed signal will be said to be successfully decomposed by cepstrum analysis if:

(1) $\underset{\sim}{s}_1(n)$ and $\underset{\sim}{s}_2(n - \underset{\sim}{n}_o)$ are similar. The first few significant amplitude peaks of $\underset{\sim}{s}_2(n - n_o)$ should be delayed by $\underset{\sim}{n}_o$ samples with respect to the corresponding peaks of $\underset{\sim}{s}_1(n)$;

(2) $\underset{\sim}{s}_1(n) \approx 0$ for $n > N_1$, where N_1 is a reasonably finite integer less than N; and

(3) $\underset{\sim}{s}_2(n - n_o) \approx 0$ for $n < \underset{\sim}{n}_o$.

For the second case, let us assume that after the first path of cepstrum analysis, the mixed signal x(n) is decomposed into a single arrival $\underset{\sim}{s}_1(n)$ and a reduced mixed signal $\underset{\sim}{x}_1(n - \underset{\sim}{n}_1)$; i.e.,

$$x(n) = \underset{\sim}{s}_1(n) + \underset{\sim}{x}_1(n - \underset{\sim}{n}_1) \qquad n \leq N, \qquad \text{(II-2)}$$

where N is the signal length of x(n).

Also, the second path of cepstrum analysis decomposed $x_1(n)$ into a single arrival, $\underset{\sim}{s}_2(n)$, and a later arrival, $\underset{\sim}{s}_3(n - \underset{\sim}{n}_2)$ (or $\underset{\sim}{x}_2(n - \underset{\sim}{n}_2)$), as follows:

$$\underset{\sim}{x}_1(n) = \underset{\sim}{s}_2(n) + s_3(n - \underset{\sim}{n}_2) \qquad n \leq N - \underset{\sim}{n}_1. \qquad \text{(II-3)}$$

(Here, when the later arrival appears to be complicated as compared to the first single arrival, it will be called a reduced mixed signal and represented by $\underset{\sim}{x}_i(n - \underset{\sim}{n}_i)$.) For this case, the first path of cepstrum analysis will be said to be successful only if the second path is successful under the criteria given for the first case, and if:

(1) $\underset{\sim}{s}_1(n)$ and $\underset{\sim}{s}_2(n - \underset{\sim}{n}_1)$ are similar,

(2) $\underset{\sim}{s}_1(n) \approx 0$ for $n > N_1$, and

(3) $\underset{\sim}{x}_1(n - \underset{\sim}{n}_1) \approx 0$ for $n < \underset{\sim}{n}_1$.

The final decomposition of x(n) for this case can be obtained by summing up equations (II-2) and (II-3) with appropriate time shift in equation (II-3) as follows:

$$x(n) = \underset{\sim}{s}_1(n) + \underset{\sim}{x}_1(n - \underset{\sim}{n}_1)$$

and $$\underset{\sim}{x}_1(n - \underset{\sim}{n}_1) = \underset{\sim}{s}_2(n - n_1) + \underset{\sim}{s}_3(n - \underset{\sim}{n}_1 - \underset{\sim}{n}_2)$$

therefore, $$x(n) = \underset{\sim}{s}_1(n) + \underset{\sim}{s}_2(n - \underset{\sim}{n}_1) + \underset{\sim}{s}_3(n - \underset{\sim}{n}_1 - \underset{\sim}{n}_2). \qquad \text{(II-4)}$$

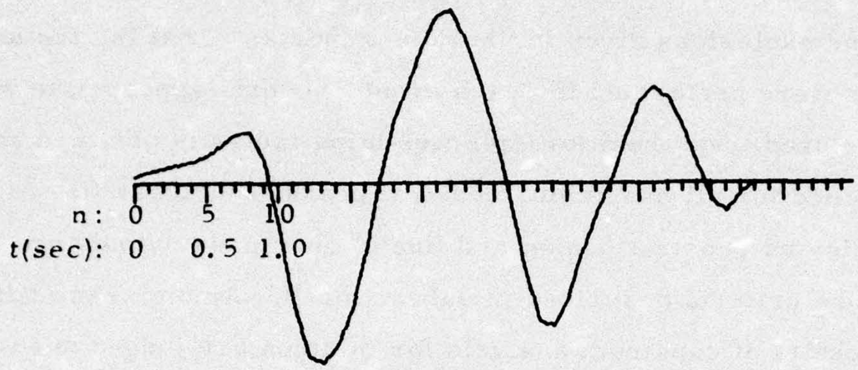
C. RESULTS

These fifteen earthquakes have been put through cepstrum analysis, event by event. Efforts to perform cepstrum analysis on these earthquakes are similar to analysis of Russian PNE events and all other presumed underground explosions given in previous reports. That is, the following procedures were performed for each event: several appropriate weighting factors are used; cepstrum for each weighting factor is obtained and carefully examined for all suspicious cepstral peaks; shortpass filters are applied to all suspicious cepstral peaks; and finally shortpass outputs are checked against those criteria described in subsection B. Among these fifteen earthquakes, results of cepstrum analysis for thirteen are judged unsuccessful. Only two events, KUR/099/04N and HON/258/14N, have been successfully cepstrum-decomposed into two single arrivals which can be expressed as follows:

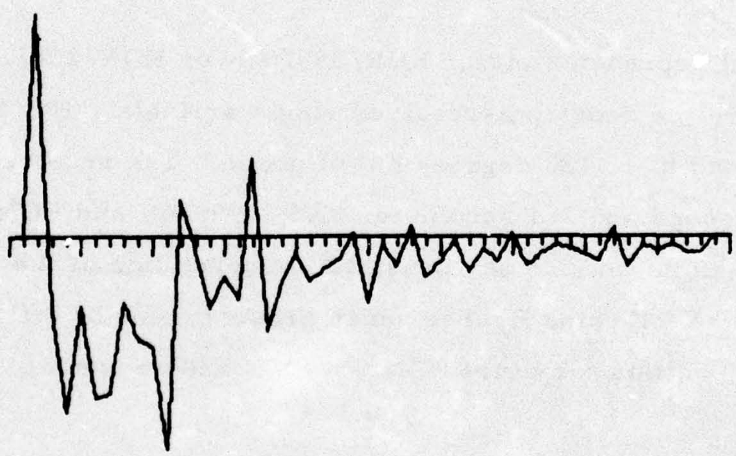
$$x(n) = \underset{\sim}{s}_1(n) + \underset{\sim}{s}_2(n - \underset{\sim}{n}_o), \qquad \text{(II-5)}$$

where x(n) represents either KUR/099/04N or HON/258/14N, and $\underset{\sim}{s}_i(n)$, $i = 1,2$ are the cepstrum-resolved single arrivals. For both events, $\underset{\sim}{s}_1$ and $\underset{\sim}{s}_2$ are found to be 180 degrees out of phase. The resolved delay times, $\underset{\sim}{n}_o$, are 0.8 second and 1.1 second for KUR/099/06N and HON/258/14N, respectively. Before we give any possible interpretation of the results, let us take a look at the following figures which present some of the results: a successful decomposition for event HON/258/14N and an unsuccessful one for KUR/213/02N.

Figure II-2 shows the waveform and the cepstrum of the signal x(n) for the event HON/258/14N. It is noticed that cepstrum does not show the definite peaks due to the possible multiple arrivals; hence the most straightforward way to filter the cepstrum is to apply the shortpass filter at any cepstral peak which is suspected to be the cepstral peak due to possible



x(n)



Cepstrum of x(n)

FIGURE II-2

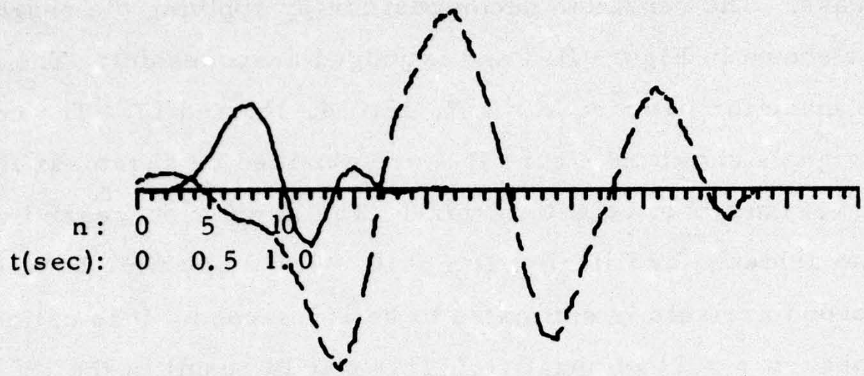
WAVEFORM AND CEPSTRUM OF x(n): HON/258/14N

multiple arrivals. Then the corresponding cepstrum resolved signals are examined to see if the signal x(n) is successfully decomposed. For this event, cepstral peaks at n = 6, 7, 11, 12, 14, 16, and 17 are decided to be the suspicious peaks. The cepstrum decomposition by applying the shortpass filter at n = 6 is shown in Figure II-3 and is judged unsuccessful. The same conclusion is made for filtering at n = 7, 12, 14, 16, and 17. The cepstrum-resolved signals shown in Figure II-4 are obtained by shortpass filtering at n = 11 and are thought to be satisfactory. The similar successful decomposition is also achieved by filtering at n = 10. The delay time between the first and the second arrivals is estimated to be 1.1 second. It is noticed that the cepstral peak at n = 11 is negative. This should result in the 180 degrees out of phase between the two resolved arrivals (Sun, 1975), as shown in Figure II-4.

The waveform and the cepstrum of the signal x(n) for the event KUR/213/02N are given in Figure II-5. Cepstral peaks at n = 8, 11, and 18 are considered to be the suspicious cepstral peaks possibly due to the multiple arrivals. Cepstrum decompositions by applying shortpass filter at n = 11 and n = 18 are presented in Figures II-6 and II-7, respectively, and are judged unsuccessful. When the shortpass filter is applied at n = 8, we obtain two resolved signals as shown in Figure II-8. According to the criteria described in Subsection B, the first resolved signal (solid line) is taken to be a single arrival and the second resolved signal (dashed line) is considered to be a reduced mixed signal. That is, after the first path of cepstrum analysis, we have:

$$x(n) = \underset{\sim}{s}_1(n) + \underset{\sim}{x}_1(n - 8) \qquad n \leq 58 \qquad \text{(II-6)}$$

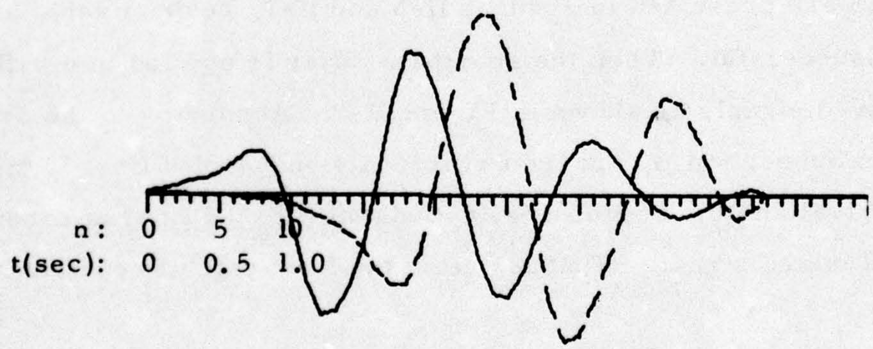
It is clear that $\underset{\sim}{s}_1$ and $\underset{\sim}{x}_1$ do satisfy the said criteria; i.e., $\underset{\sim}{s}_1(n) \approx 0$ for $n > N_1$ (here $N_1 \approx 20$) and $x_1(n - 8) \approx 0 \quad n < \underset{\sim}{n}_o$ (here $\underset{\sim}{n}_o = 8$). Now, the second path of cepstrum analysis is applied to the reduced mixed signal $\underset{\sim}{x}_1$.



Unsuccessful: filtering at n=6

FIGURE II-3

CEPSTRUM DECOMPOSITION OF x(n): HON/258/14N

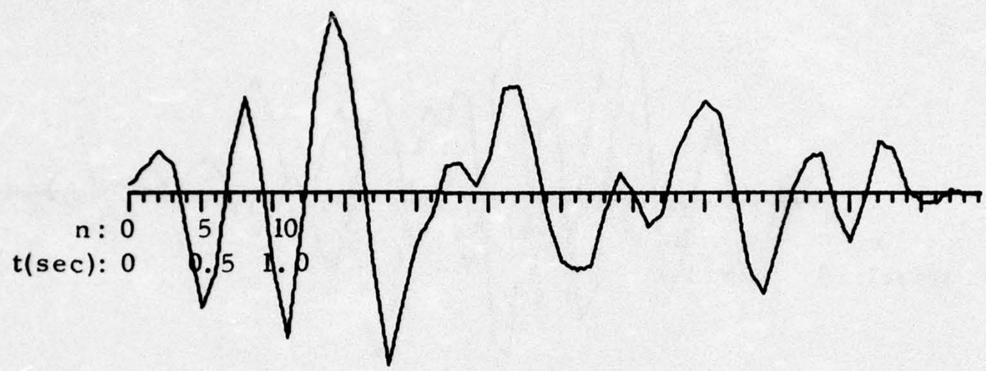


Successful: filtering at n=11

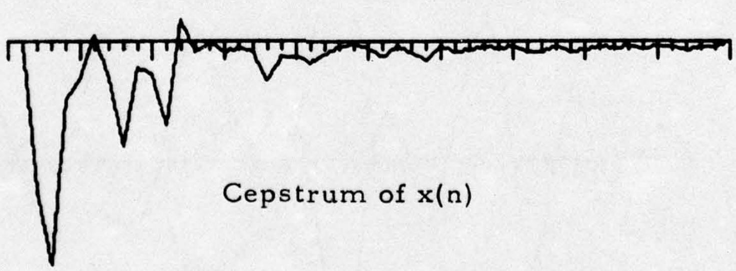
$x(n) = \underset{\sim}{s}_1(n) + \underset{\sim}{s}_2(n-11)$

FIGURE II-4

CEPSTRUM DECOMPOSITION OF x(n): HON/258/14N



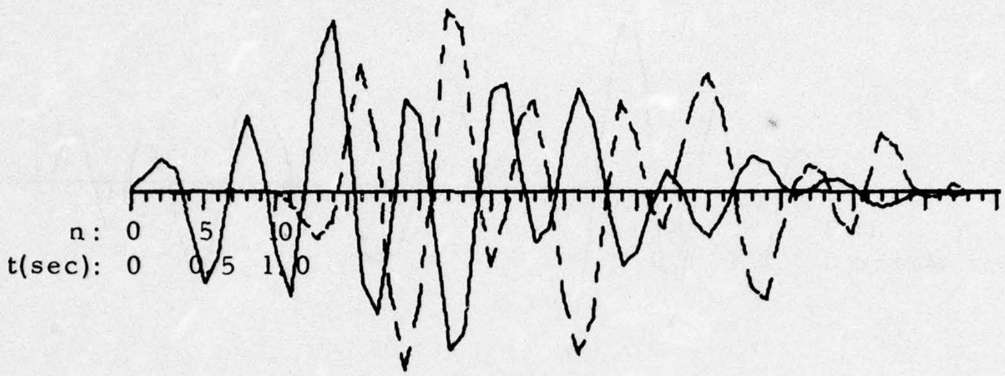
x(n)



Cepstrum of x(n)

FIGURE II-5

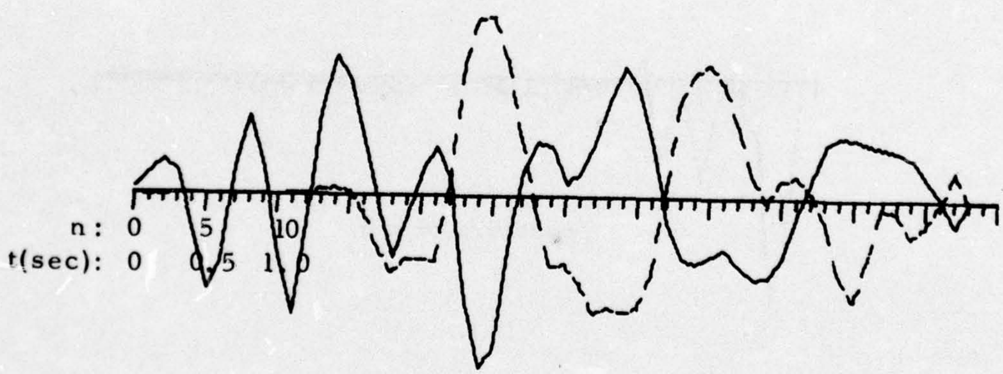
WAVEFORM AND CEPSTRUM OF x(n): KUR/213/02N



Unsuccessful: filtering at n=11

FIGURE II-6

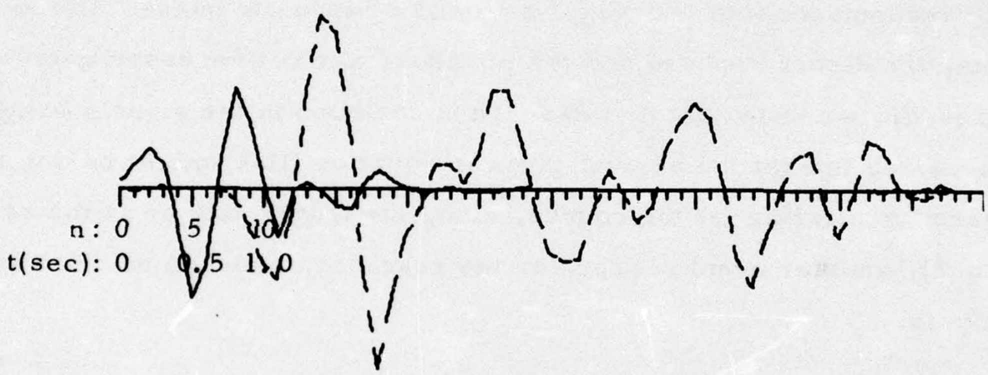
CEPSTRUM DECOMPOSITION OF x(n): KUR/213/02N



Unsuccessful: filtering at n=18

FIGURE II-7

CEPSTRUM DECOMPOSITION OF x(n): KUR/213/02N



Unsuccessful: filtering at n=8

FIGURE II-8

CEPSTRUM DECOMPOSITION OF x(n): KUR/213/02N

However, after all possible trials, no successful cepstrum decomposition can be obtained for $\underline{x}_1$. Therefore, it is concluded that the second path of cepstrum analysis has failed. This, in turn, implies that the first path of cepstrum analysis on x is unsuccessful. Hence, for this event, no successful final cepstrum decomposition is found.

Unsuccessful cepstrum decompositions of the majority of these earthquakes, thirteen out of fiteen, are expected and understandable, since the signal lengths of these earthquakes have been chosen in such a way that the pP-phase is excluded. The situation requiring explanation here concerns the events KUR/099/04N and HON/258/14N, which cepstrum analysis successfully decomposes into two single arrivals of opposite phase. Unlike explosions, the direct P-phase and the pP-phase are not necessarily out of phase. Moreover, we know that no pP-phase is included in the signals being analyzed. Therefore, the second arrival given in equation (II-5) might be due to these causes: scattering (at the source, along the travel path or at the recording station), another event nearby, or the result of misdecomposition by cepstrum analysis.

D. CONCLUSIONS

During the course of cepstrum analysis of these fifteen earthquakes, it has been found that the earthquake signal is more difficult to deal with than the explosion signal. This difficulty is caused by two factors: the earthquake signal usually is more complicated and the criteria for the earthquakes cannot be made as restricted as those for explosions. Even so, among the fifteen earthquakes being analyzed here, the percentage of possible misdecomposition by cepstrum analysis is low: about 10% at the worst. It is possible that the misdecomposition comes from the inherent defect of the complex cepstrum technique. However, it is more likely that this is due to the lack of more restricted criteria for analyzing earthquake signals.

Therefore, it is believed that the misdecomposition by cepstrum analysis is unlikely, especially if the criteria can be made more restricted and if the analyst follows those criteria closely.

SECTION III
CEPSTRUM ANALYSIS OF TWO EKZ EVENTS

A. INTRODUCTION

In our previous analysis of the teleseismic short period P-waves of presumed underground explosions in Russia, eastern Kazakh (EKZ) events (Lane and Sun, 1974b; Sun, 1975), and PNE events (Lane and Sun, 1975), we usually used signals recorded at one single subarray (with best signal-to-noise ratio) in NORSAR (or LASA). The reason was simple and practical. Second, for EKZ events, signals recorded at NORSAR were the best; and for PNE events only LASA data were usable in most cases. However, when analyzing an event using only one signal recorded at a single station, the following question always exists: whether the cepstrum-decomposed multiple arrivals really originate at the source(s) or whether they just result from some other mechanism, such as local scattering. This is the question to which the complex cepstrum technique alone has no answer. Intuitively, however, if we can analyze an event using signals recorded at several different stations, the results of cepstrum analysis which are common to all stations are more likely to originate at the source(s). Preliminary results using signals recorded at two stations were presented in a previous report (Lane and Sun, 1975). There, we found that for some EKZ and PNE events, both NORSAR and LASA data were available and usable. Between them, the results of cepstrum analysis were found quite consistent. It is the purpose of this section to elaborate the above idea of analyzing an event using signals recorded at several stations. Here, two EKZ events will be analyzed using signals recorded at several different NORSAR subarrays.

B. SELECTION OF SUBARRAY BEAM TRACES

Cepstrum analysis of an event using signals recorded at different stations probably will give more convincing results if these stations are in different azimuths. However, the availability of the accessible yet usable data has been preventing us from doing so. It seems that the next best approach is to use signals recorded at different sensors in a large array station. Although the distance between two NORSAR subarrays is about 100 km maximum, due to the local geology, the variations of the recorded signals from subarray to subarray are quite noticeable for the EKZ events, especially between the subarrays in the west side and those in the east side of NORSAR (Barnard and Whitelaw, 1972; Ringdal and Whitelaw, 1973). Figure III-1 shows teleseismic short period P-waves of the event EKZ/294/06N recorded at twenty-two NORSAR subarrays. Therefore, we have decided to use signals recorded at several NORSAR subarrays.

Two EKZ events, EKZ/294/06N and EKZ/333/06N, are chosen to be analyzed. The subarray signals are selected according to the following guidelines:

- Hopefully, a good mixture of subarray signals from both east and west sides of NORSAR can be obtained.
- The subarray signal-to-noise ratio (SNR) possibly is greater than 18 dB. (This lower limit in SNR is set based on the conclusion obtained in the previous study on the effect of noise (Sun, 1975).

Table III-1 presents the source information for these two events. Also given in this table are the SNR's of the selected subarray signals. In order to show the relative locations of these selected subarrays, NORSAR array configuration is given in Figure III-2.

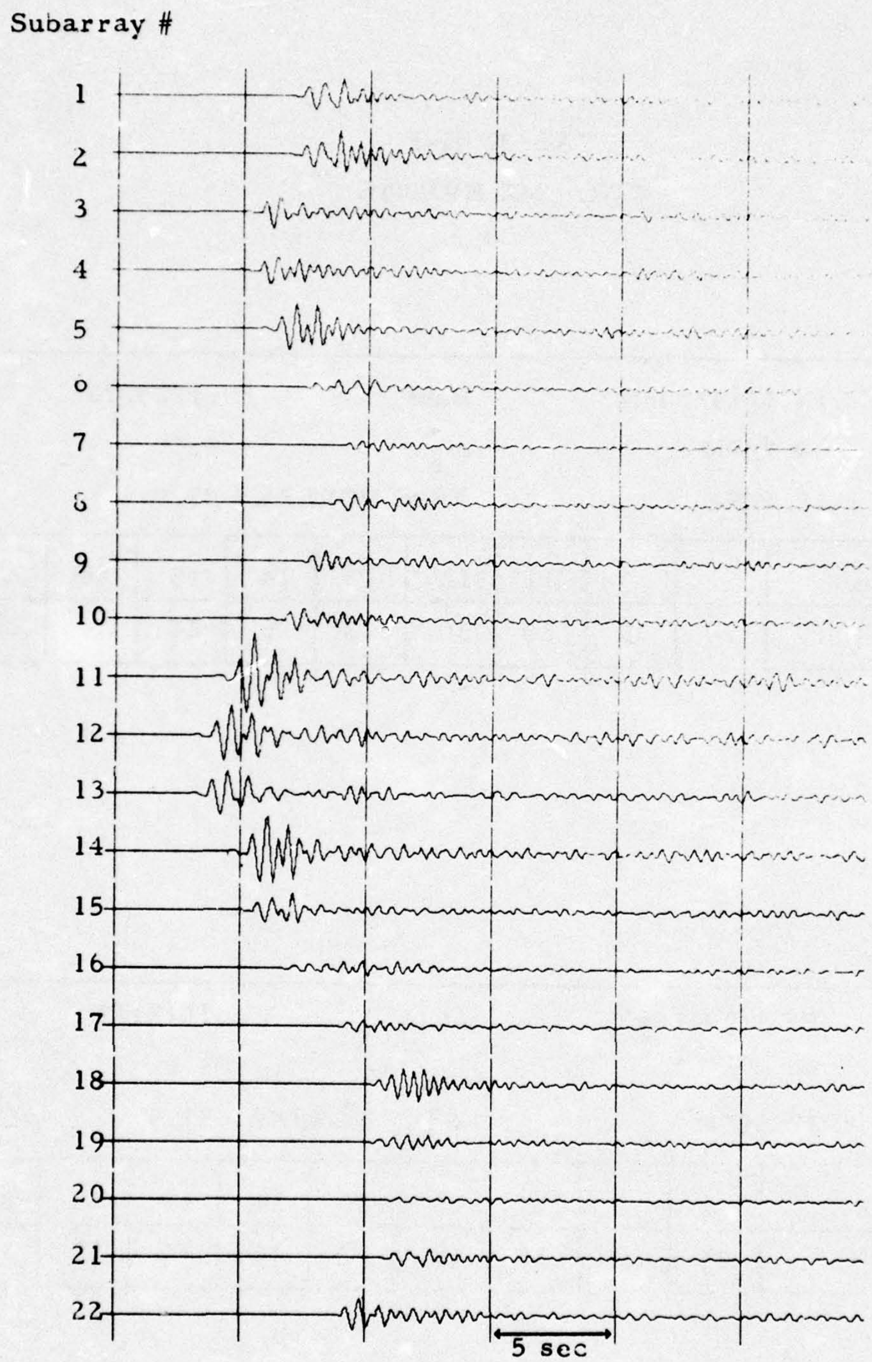


FIGURE III-1

TYPICAL SHORT-PERIOD P-WAVES OF EKZ EVENT RECORDED AT NORSAR SUBARRAYS

TABLE III-1

TWO EKZ EVENTS

Event I. D.: EKZ/333/06N				Date : 11/29/71					
Latitude : 49.79°N				m_b : 5.5					
Longitude : 78.09°E				Δ° to NORSAR: 37.9					
Subarray	2	5	11	12	13	14	15	18	22
SNR (dB)	24	30	30	30	28	25	24	24	20

Event I. D.: EKZ/294/06N				Date : 10/21/71					
Latitude : 50.0°N				m_b : 5.6					
Longitude : 77.59°E				Δ° to NORSAR: 37.5					
Subarray	2	5	11	12	13	14	15	18	22
SNR (dB)	25	23	26	18	18	24	20	18	18

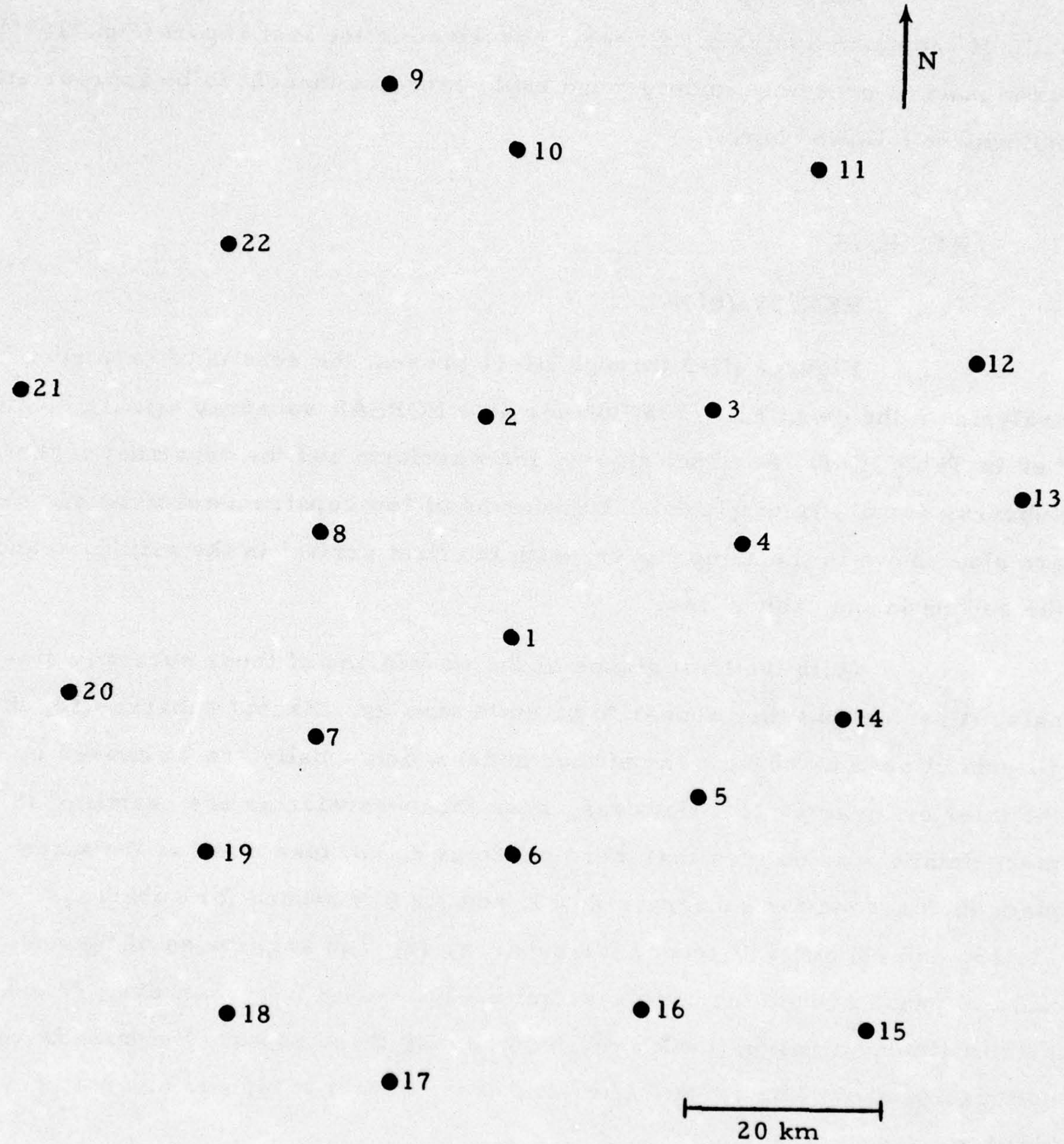


FIGURE III-2

NORSAR SHORT-PERIOD ARRAY

Here, again, we must have some criteria for judging the results of cepstrum analysis. Criteria described in the last report (Sun, 1975) for signals of presumed underground explosions are thought to be appropriate and will be followed here.

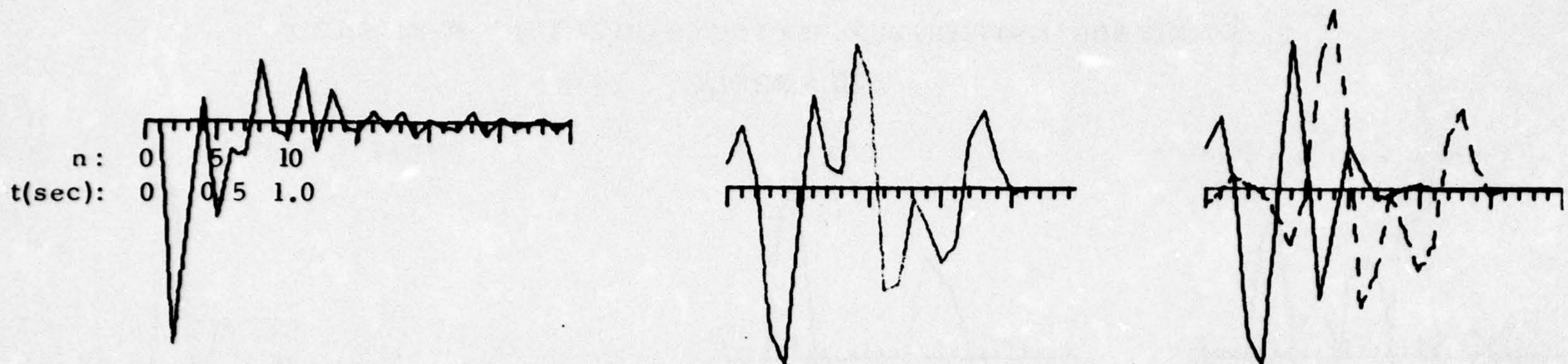
C. RESULTS

1. EKZ/333/06N

Figures III-3 through III-11 present the results of cepstrum analysis on the event EKZ/333/06N for nine NORSAR subarray signals identified in Table III-1. For each figure, the waveform and the cepstrum of the subarray signal are displayed. Waveforms of two cepstrum-resolved signals are also shown in the same figure, with the first arrival in the solid line and the second in the dashed line.

With the first glance of the waveforms of these subarray signals, it seems that they appear to be quite similar. Except subarray 18, they all exhibit obvious phasing (amplitude node) which usually can be caused by the interfering arrivals. However, when these waveforms are examined in more detail, it is noticed that these phasings do not take place at the same place (0.8 second for subarrays 2, 14, and 15; 0.9 second for subarrays 5, 11, 13, and 22; and 1.0 second for subarray 12); and amplitudes of the node and two peaks around the node vary quite a lot among the subarrays. Moreover, the amplitude variation (peak amplitude) among these subarray signals is very noticeable, about 3 to 1. So, after all, these subarray signals are not very similar.

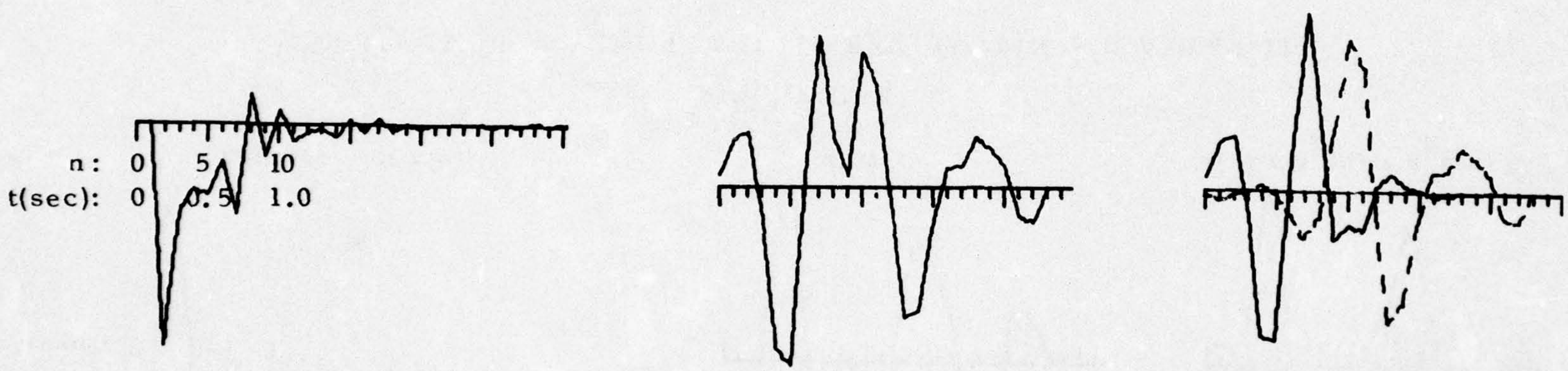
No periodic appearances of cepstral peaks are observed in the cepstra of these signals. This is thought to be reasonable, since the possible second arrival can be expected to be non-identical to the first for the real seismic signal (Sun, 1975). Therefore, the cepstrum is shortpass-filtered



cepstrum of x(n) x(n) $x(n) = s_p(n) + s_p p(n-5)$

FIGURE III-3

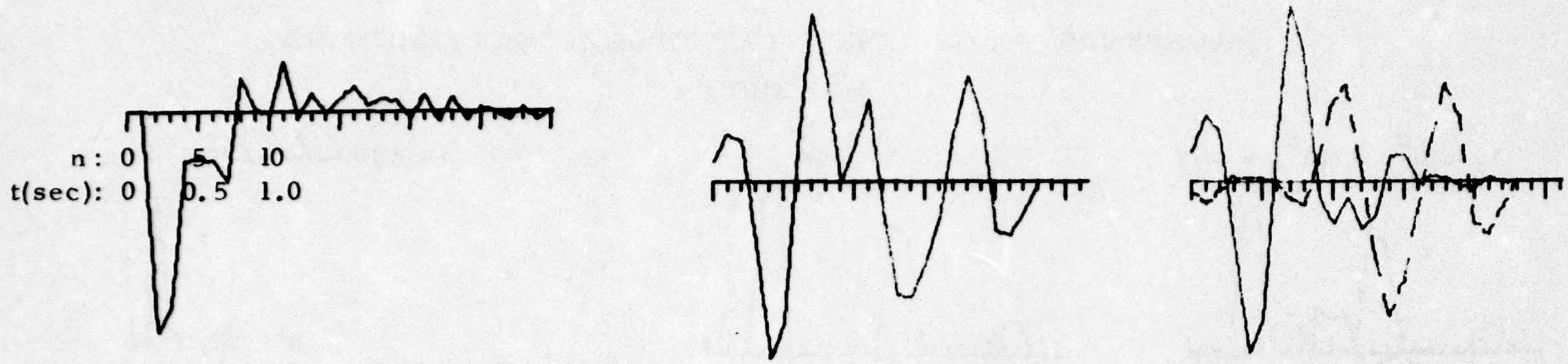
CEPSTRUM ANALYZED RESULTS: EKZ/333/06N SUBARRAY-2



cepstrum of x(n) x(n) $x(n) = s_p(n) + s_p p(n-5)$

FIGURE III-4

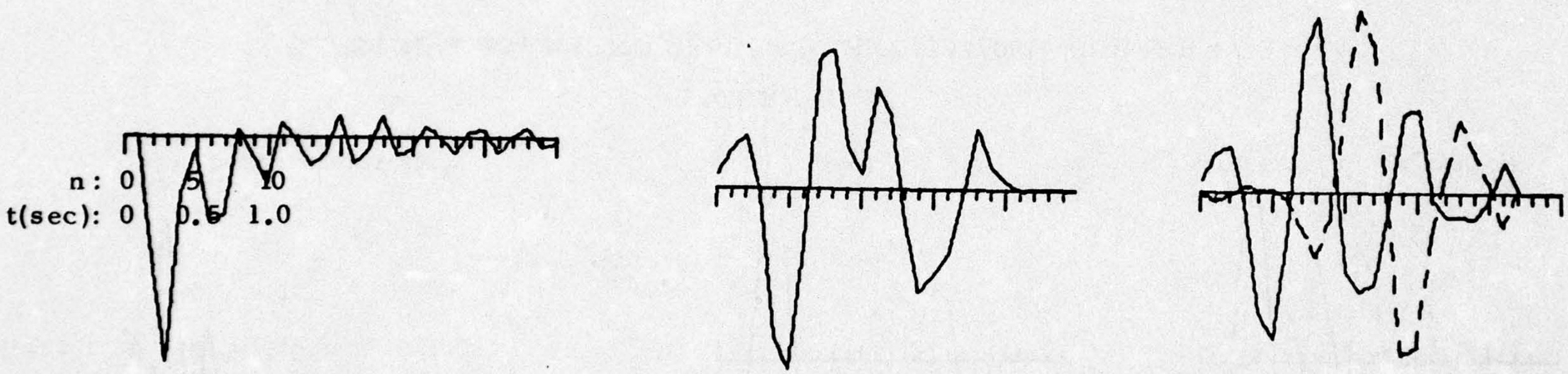
CEPSTRUM ANALYZED RESULTS: EKZ/333/06N SUBARRAY-5



cepstrum of x(n) x(n) $x(n) = s_p(n) + s_p p(n-7)$

FIGURE III-5

CEPSTRUM ANALYZED RESULTS: EKZ/333/06N SUBARRAY-11



cepstrum of x(n) x(n) $x(n) = s_p(n) + s_p p(n-6)$

FIGURE III-6

CEPSTRUM ANALYZED RESULTS: EKZ/333/06N SUBARRAY-12

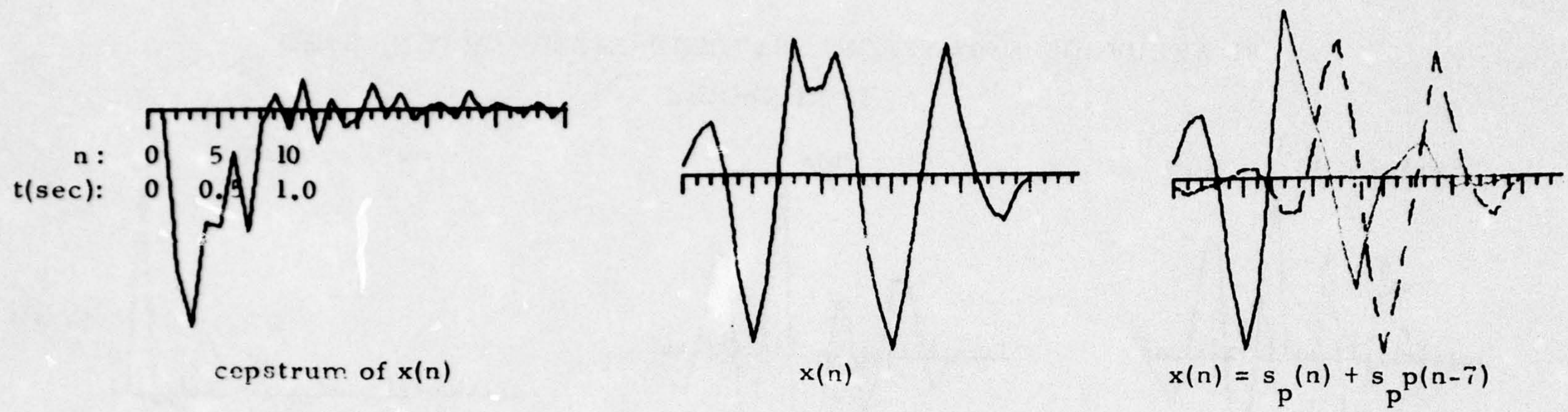


FIGURE III-7

CEPSTRUM ANALYZED RESULTS: EKZ/333/06N SUBARRAY-13

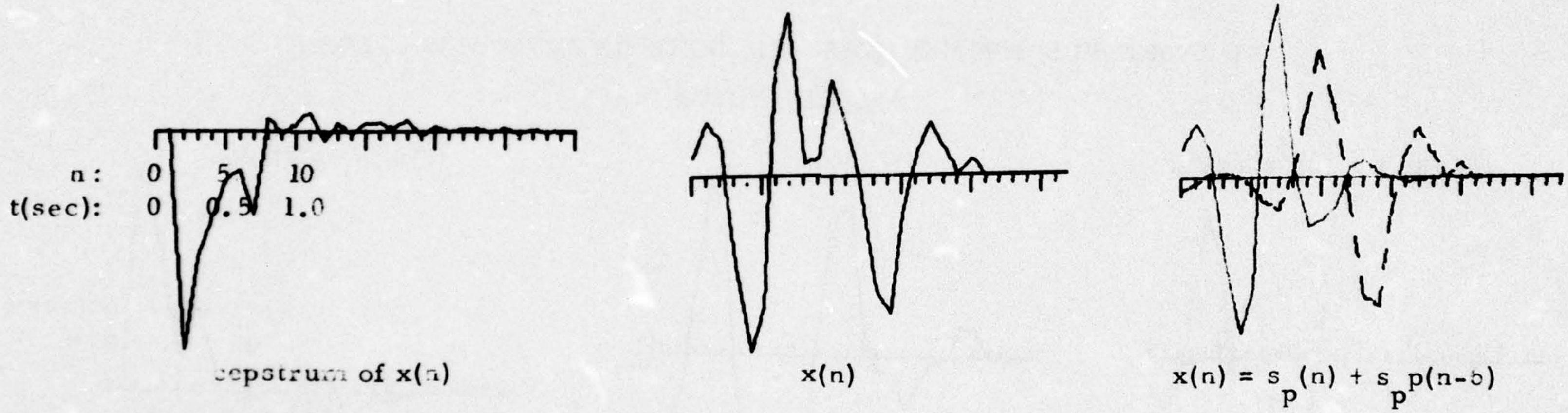


FIGURE III-8

CEPSTRUM ANALYZED RESULTS: EKZ/333/06N SUBARRAY-14

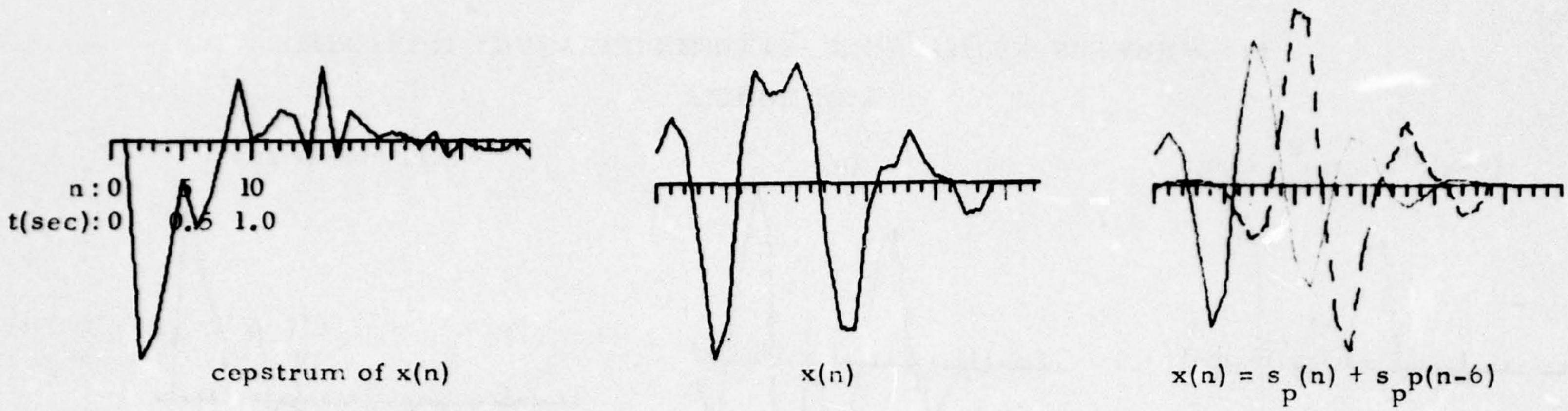


FIGURE III-9

CEPSTRUM ANALYZED RESULTS: EKZ/333/06N SUBARRAY-15

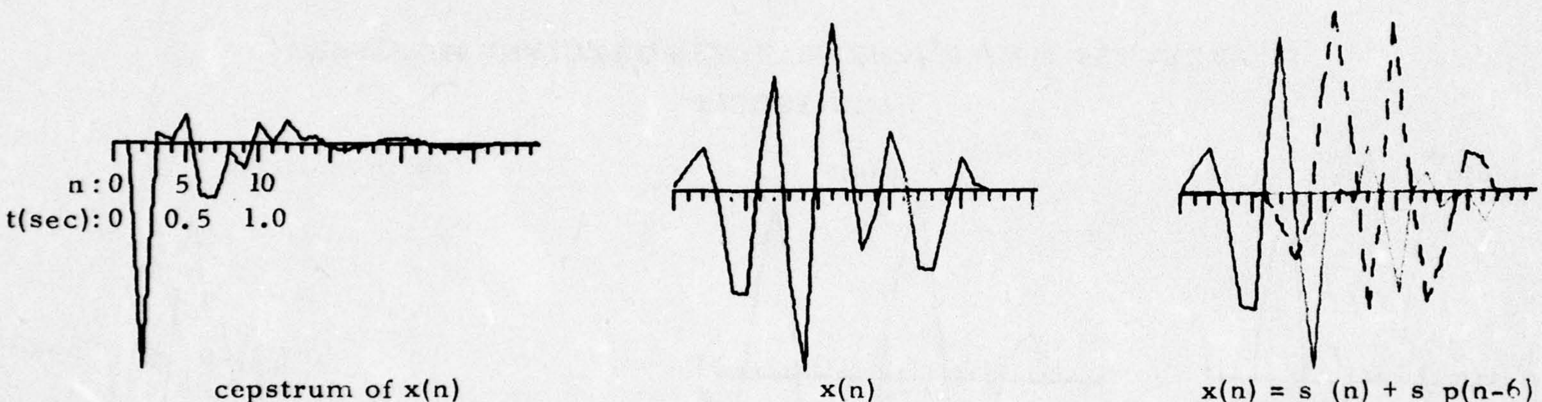


FIGURE III-10

CEPSTRUM ANALYZED RESULTS: EKZ/333/06N SUBARRAY-18

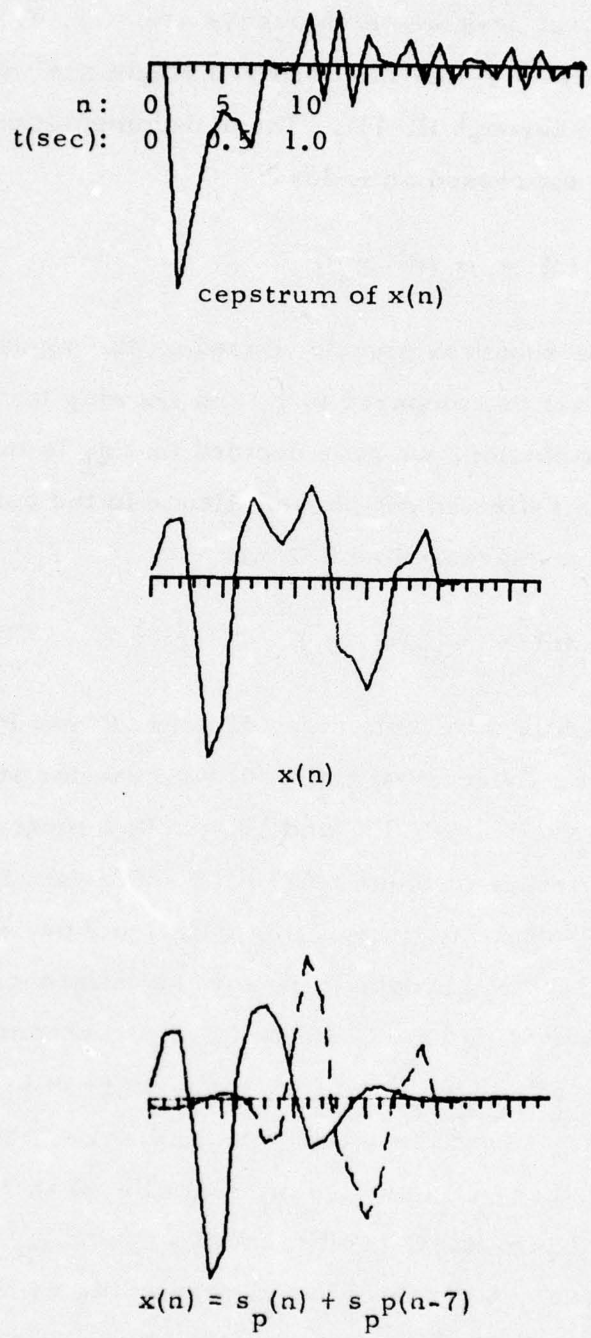


FIGURE III-11

CEPSTRUM ANALYZED RESULTS: EKZ/333/06N SUBARRAY-22

at each suspicious cepstral peak. The cepstrum decomposition by filtering at the first suspicious cepstral peak -- which occurs at n = 5, 6, or 7, differing from subarray to subarray -- yields two resolved single arrivals as shown in each figure (Figures III-3 through III-11). These decompositions are judged to be successful and can be expressed as follows:

$$x(n) = \underset{\sim}{s}_1(n) + \underset{\sim}{s}_2(n - \underset{\sim}{n}_o), \qquad \text{(III-1)}$$

where x(n) represents the subarray signal. Based on the opposite phase of the resolved second arrival as compared to $\underset{\sim}{s}_1$ and knowing that this event is a presumed underground explosion, we have decided that $\underset{\sim}{s}_1$ is the direct P-phase and that $\underset{\sim}{s}_2$ is the surface reflected pP-phase. Hence in the corresponding figures, equation (III-1) is expressed as follows:

$$x(n) = s_p(n) + s_{pP}(n - \underset{\sim}{n}_o). \qquad \text{(III-2)}$$

Three slightly different values of the resolved P-pP delay time, $\underset{\sim}{n}_o$, are found among these subarray signals: 0.5 second for subarrays 2 and 5; 0.6 second for subarrays 12, 14, 15, and 18; and 0.7 second for subarrays 11, 13, and 22. If the average of these resolved P-pP delay times, 0.6 second, is taken to be the P-pP delay time of this event, the deviation of 0.1 second found in the resolved P-pP delay time for the different subarrays is acceptable because the sampling rate is 10 samples per second here. The peak-to-peak amplitude ratio of s_{pP} to s_P is in the range of 0.82 to 1.05. It is hard to say what is the cause of this 20% variation among these subarray signals, although the surface reflection coefficient of 0.82 to 1.05 is not an unreasonable value. The similarity coefficient of s_{pP} and s_P ranges from 0.75 to 0.9, which figures are reasonable and compatible with those found in the last report (Sun, 1975). Finally, the amplitude (peak amplitude) variation among the resolved direct P-phase, s_P, is found to be about 3.5 to 1. This

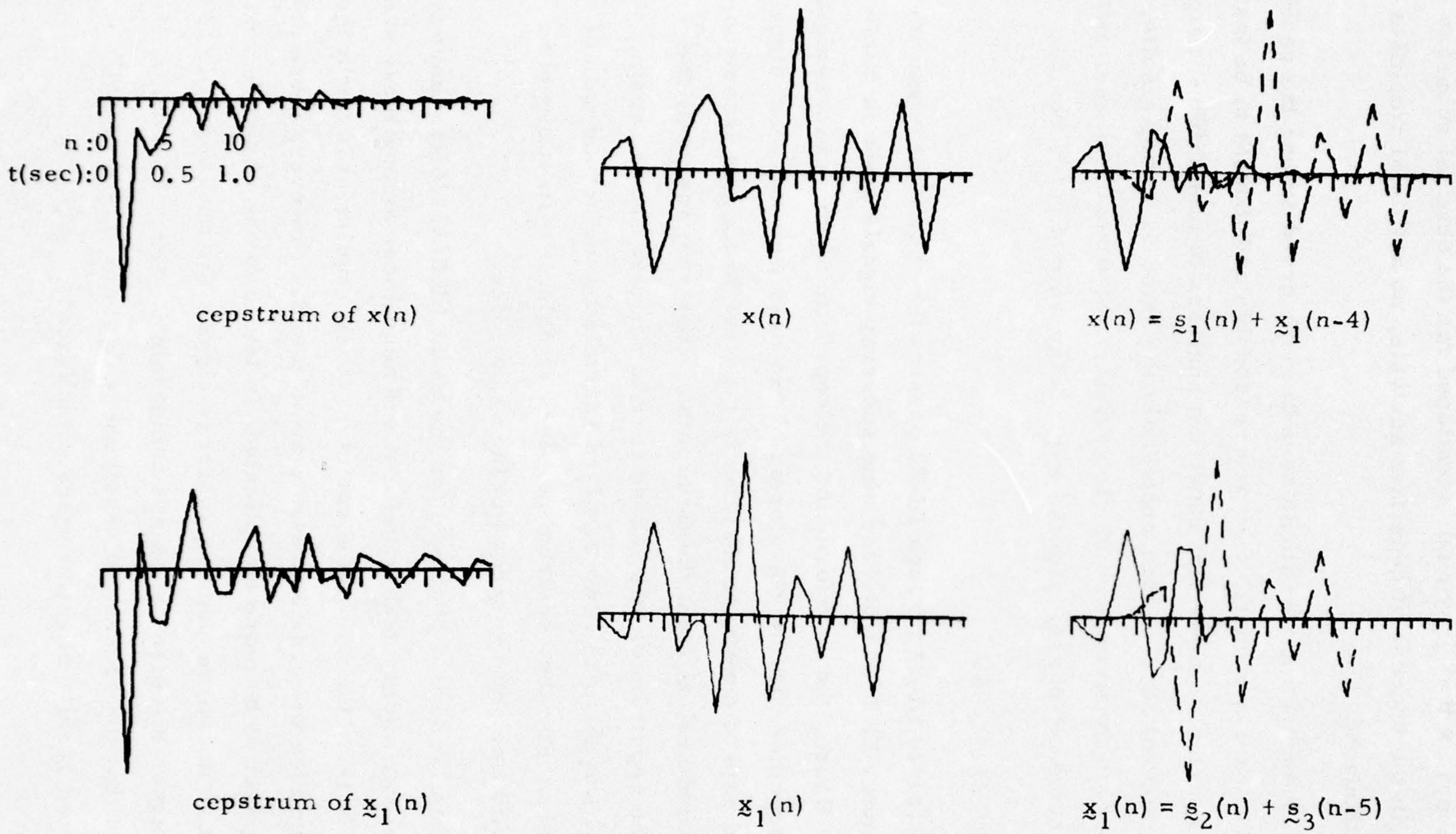
is in the same order as that previously mentioned for the original subarray signals. Thus, in the process of cepstrum analysis, no artificial amplification has been introduced.

Although some variations have been observed among the results of nine different subarray signals, they are reasonable and thought to be insignificant. The important thing is that cepstrum analyses of nine different signals for the same event have yielded practically the same essential results, namely, that they all consist of two single arrivals, the direct P-phase, and the surface reflected pP-phase, with the P-pP delay time of 0.6 second.

2. EKZ/294/06N

Figures III-12 through III-20 present the results of cepstrum analysis of the event EKZ/294/06N for nine subarray signals given in Table III-1. For each figure, the waveform and the cepstrum of the subarray signals are displayed, together with the waveforms of two cepstrum-resolved signals. When the second path of cepstrum analysis is required to further decompose the resolved second arrival from the first path of cepstrum analysis, the waveform and the cepstrum of this second arrival are also shown, again, together with the waveforms of two resolved arrivals by the second path of cepstrum analysis. For the cepstrum resolved signals, the first signal is plotted in the solid line and the second in the dashed line.

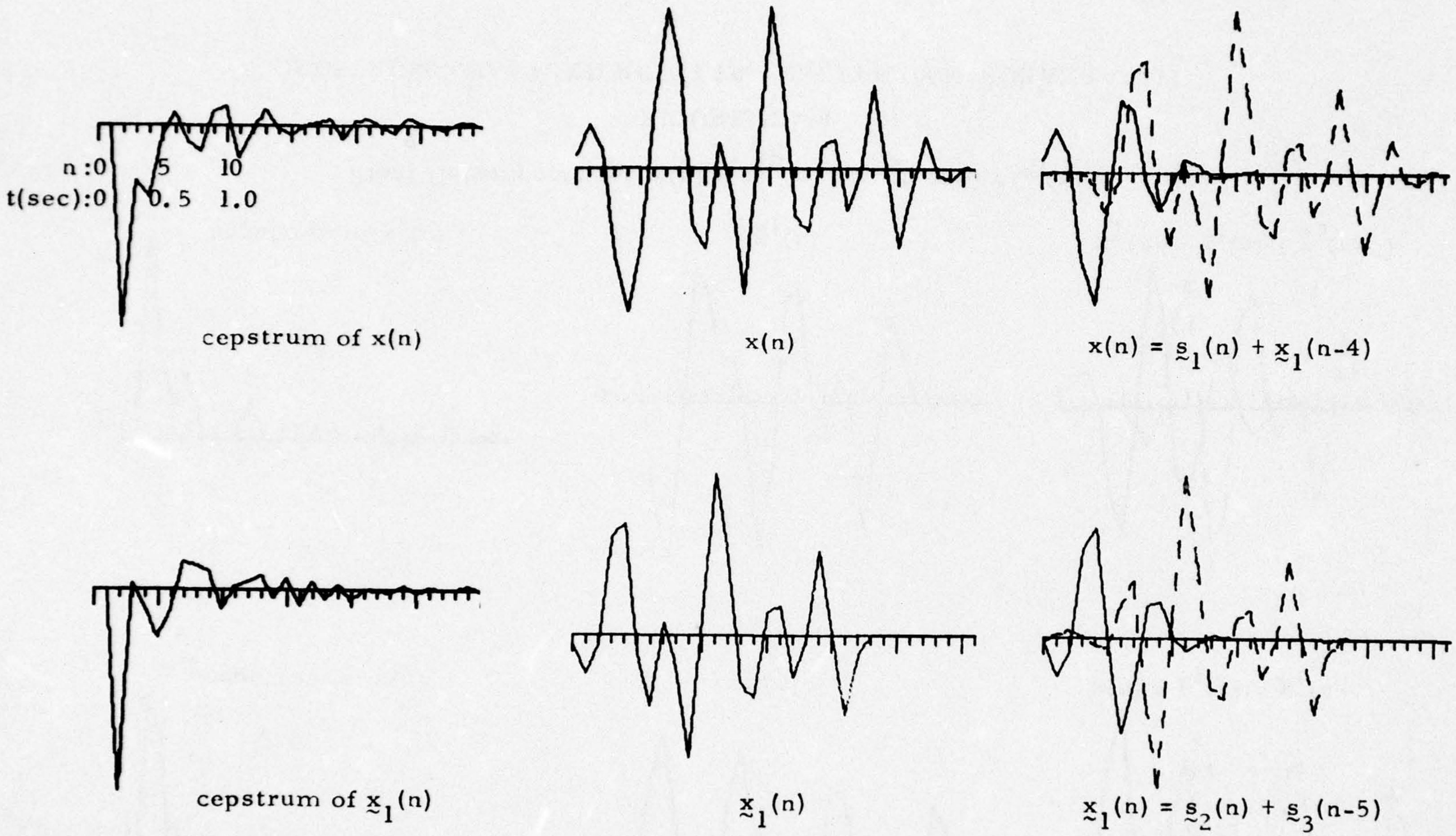
Similar to that observed for the event EKZ/333/06N, there is noticeable signal variations, both waveform and amplitude, among these subarray signals. In fact, the amplitude variation (peak amplitude) is about the same as that found for the previous event, about 3 to 1. However, these subarray signals appear to be more complicated, in terms of the waveform and signal length, than the corresponding subarray signals for the event EKZ/333/06N; and their signal-to-noise ratios are comparably lower. Therefore, it can be expected that the process of cepstrum analysis on this event will be more difficult and results might be more complicated.



Final Decomposition: $x(n) = s_{1p}(n) + s_{1p}p(n-4) + \underset{\sim}{s}_3(n-9)$

FIGURE III-12

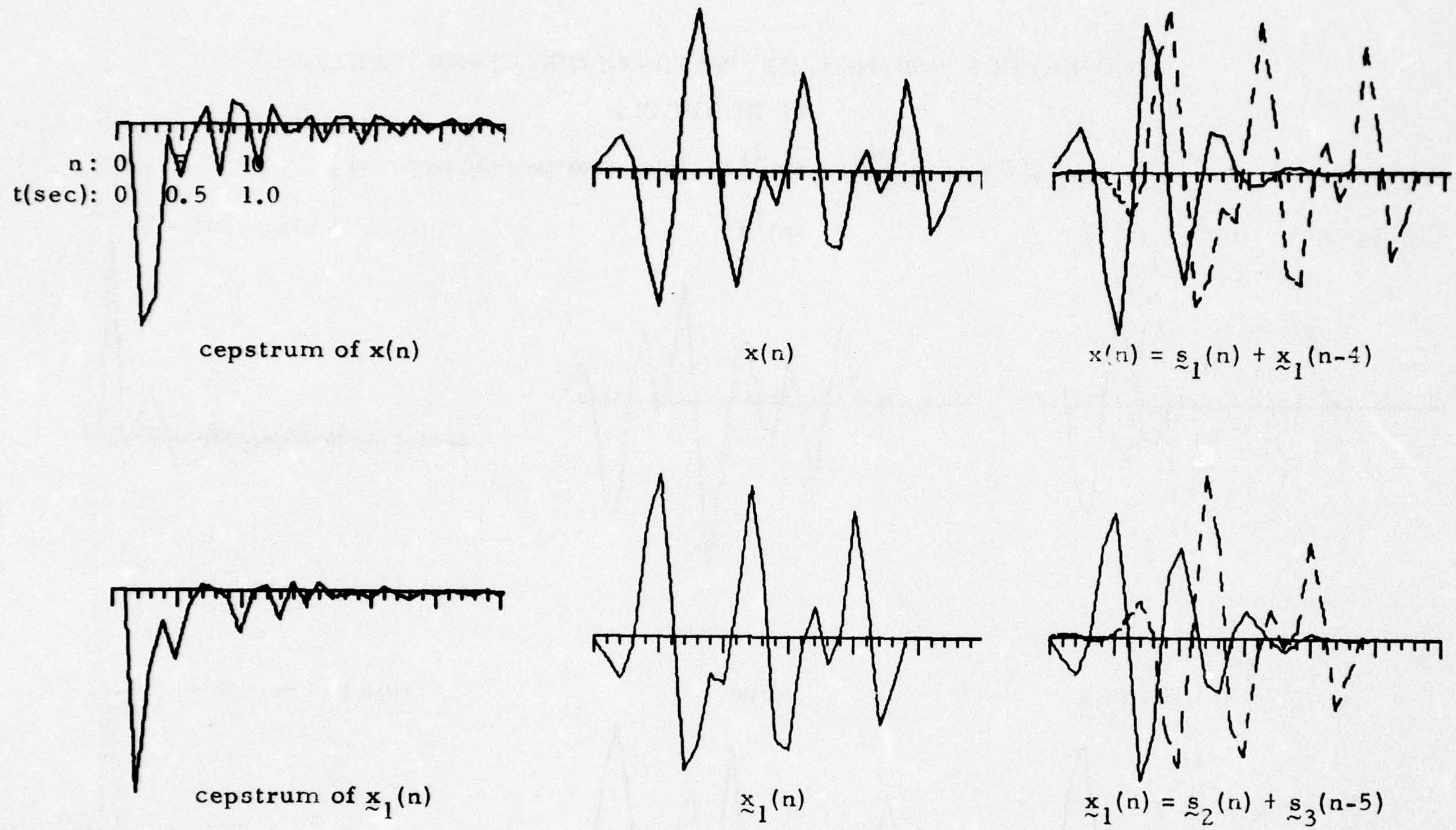
CEPSTRUM ANALYZED RESULTS: EKZ/294/06N SUBARRAY-2



Final Decomposition: $x(n) = s_{1p}(n) + s_{1p}p(n-4) + \underset{\sim}{s}_3(n-9)$

FIGURE III-13

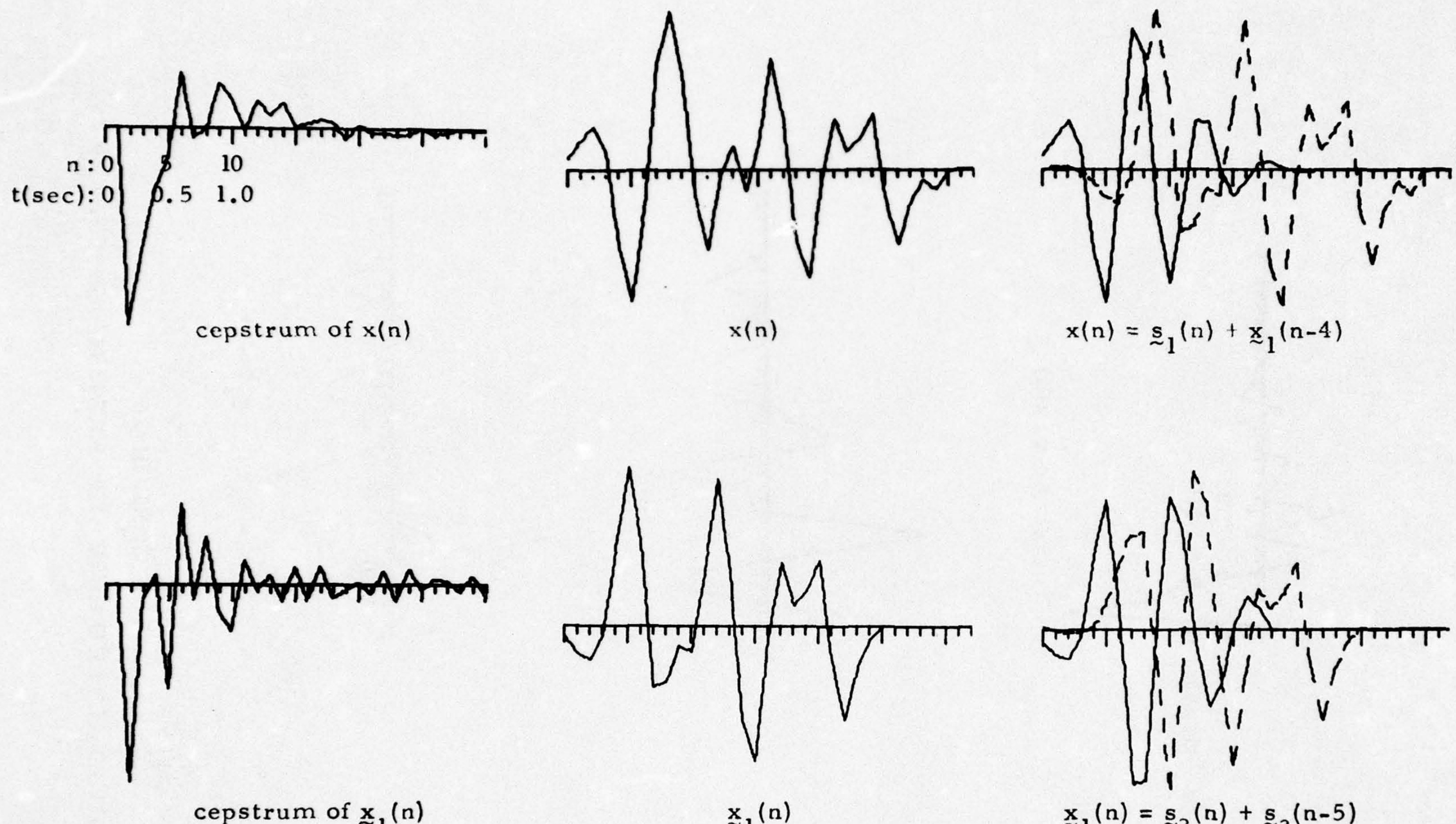
CEPSTRUM ANALYZED RESULTS: EKZ/294/06N SUBARRAY-5



Final Decomposition: $x(n) = s_{1p}(n) + s_{1p}p(n-4) + \underset{\sim}{s}_3(n-9)$

FIGURE III-14

CEPSTRUM ANALYZED RESULTS: EKZ/294/06N SUBARRAY-11



Final Decomposition: $x(n) = s_{1p}(n) + s_{1p}p(n-4) + \underset{\sim}{s}_3(n-9)$

FIGURE III-15

CEPSTRUM ANALYZED RESULTS: EKZ/294/06N SUBARRAY-12

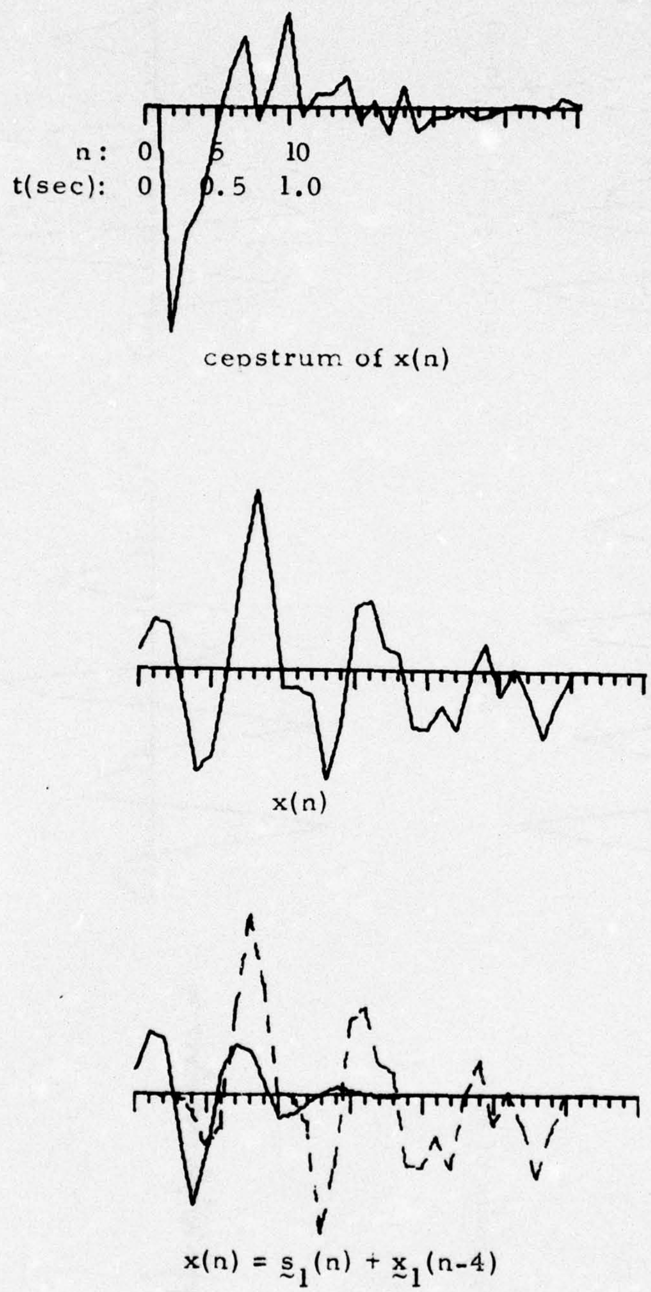
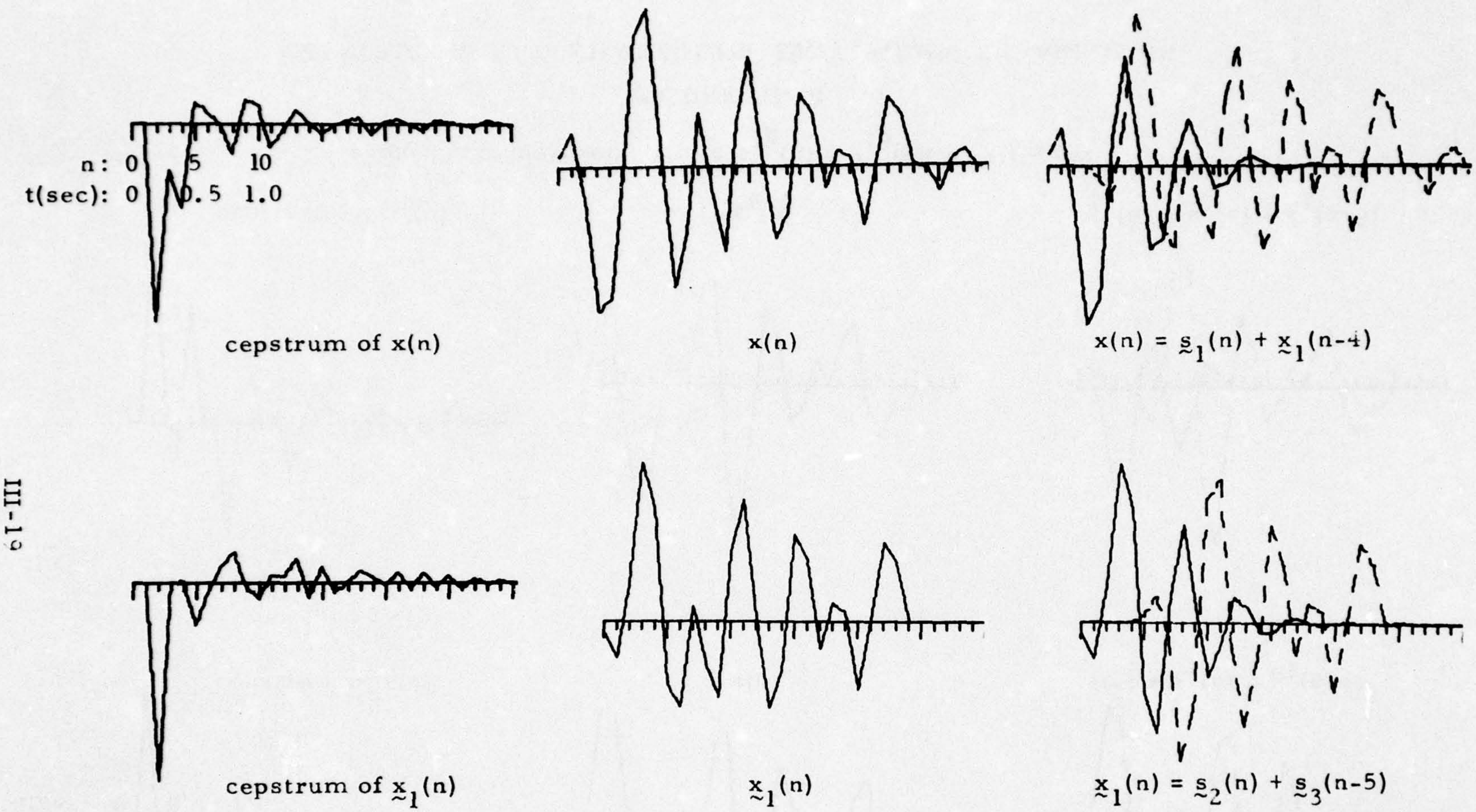


FIGURE III-16

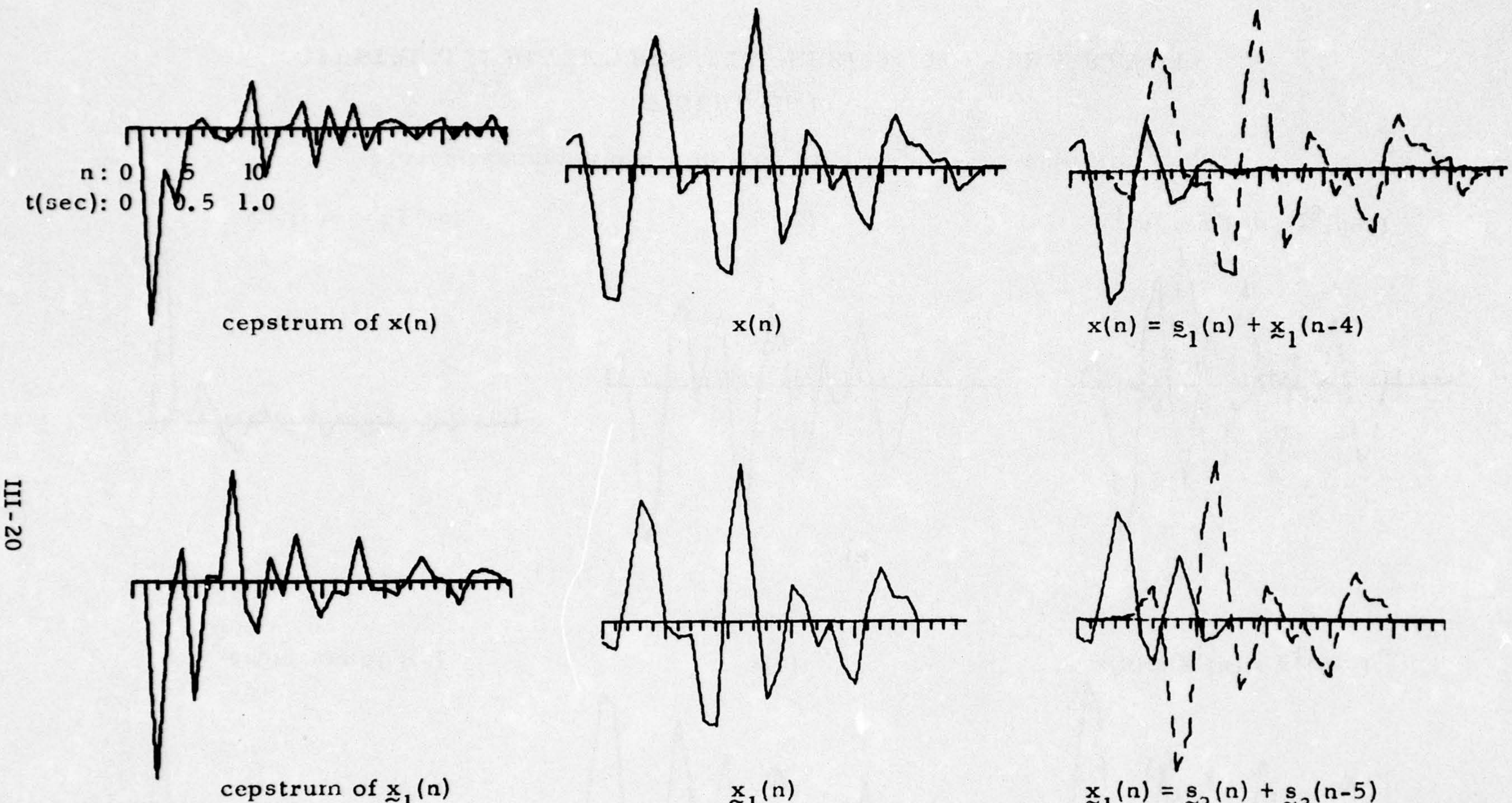
CEPSTRUM ANALYZED RESULTS: EKZ/294/06N SUBARRAY-13



Final Decomposition: $x(n) = s_{1p}(n) + s_{1p}p(n-4) + \underset{\sim}{s}_3(n-9)$

FIGURE III-17

CEPSTRUM ANALYZED RESULTS: EKZ/294/06N SUBARRAY-14



Final Decomposition: $x(n) = s_{1p}(n) + s_{1p}p(n-4) + \underset{\sim}{s}_3(n-9)$

FIGURE III-18

CEPSTRUM ANALYZED RESULTS: EKZ/294/06N SUBARRAY-15

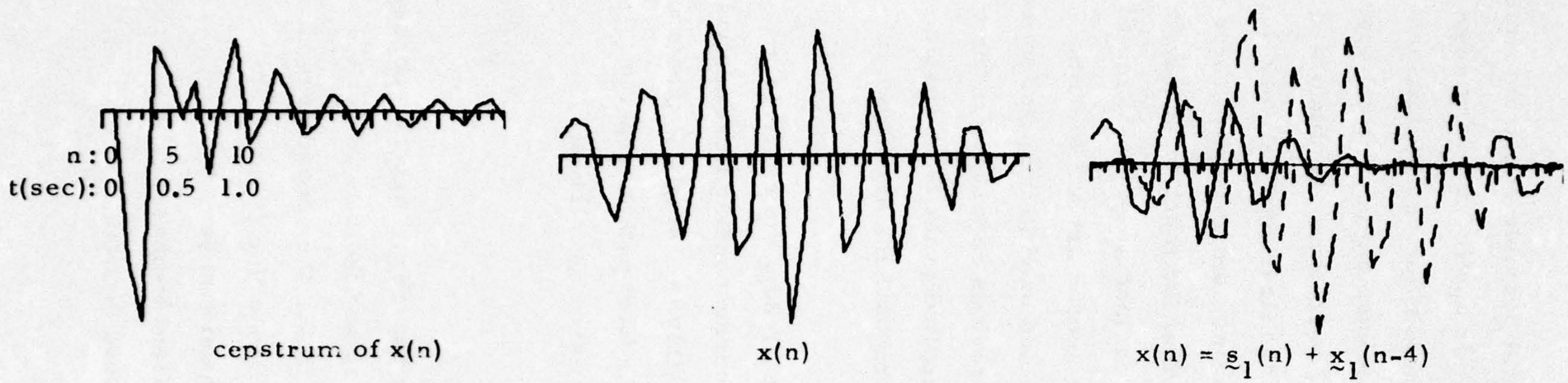


FIGURE III-19

CEPSTRUM ANALYZED RESULTS: EKZ/294/06N SUBARRAY-18

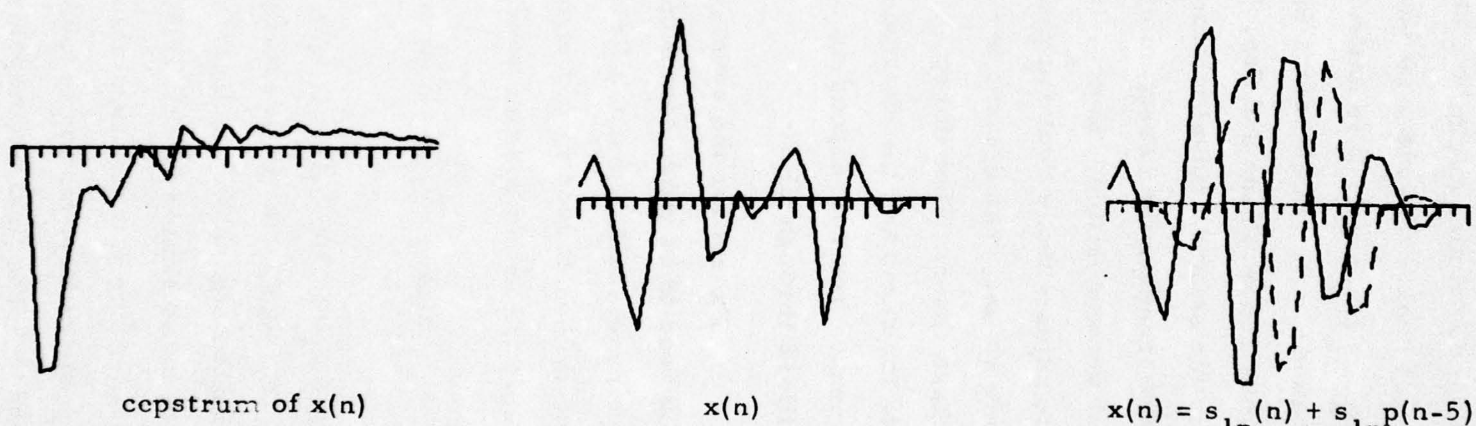


FIGURE III-20

CEPSTRUM ANALYZED RESULTS: EKZ/294/06N SUBARRAY-22

Cepstra of these signals show several possible cepstrum times to filter the cepstrum. Again, the shortpass filter is applied at every suspicious cepstral peak. However, no successful decomposition can be obtained with shortpass filtering. It is noticed that the first suspicious cepstral peak occurs around $n = 4$, which seems too close to the zero time. As discussed in a previous report (Lane and Sun, 1974b), when the first cepstral peak due to the possible second arrival is close to the zero line, the shortpass filter in general will truncate the cepstrum of the first arrival too much to achieve a successful decomposition. Hence, in that report, a special type of comb filter, which adjusts those cepstral peaks due to the second arrival to some appropriate values, was derived for this situation and used in conjunction with the shortpass filter. Therefore, as done in the previous report, here the combination of the comb and the shortpass filters is applied at the first suspicious cepstral peak. The corresponding cepstrum decompositions are shown in Figures III-12 through III-20.

Except for the subarray 22 (Figure III-20), the resolved second arrivals appear to be more complicated than the corresponding first arrivals. Hence, we have decided that the first arrival possibly is a single P-phase and the second is the reduced mixed signal. Thus, the first path of cepstrum analysis yields the decomposition which can be expressed as follows:

$$x(n) = \underset{\sim}{s}_1(n) + \underset{\sim}{x}_1(n - \underset{\sim}{n}_o), \qquad \text{(III-3)}$$

where $x(n)$, $\underset{\sim}{s}_1(n)$, and $\underset{\sim}{x}_1(n - \underset{\sim}{n}_o)$ with $\underset{\sim}{n}_o$ estimated to be 0.4 second, represent the subarray signal, the first arrival single phase, and the second arrival reduced mixed signal, respectively. For subarray 22, the second arrival appears to be as simple as the first, and the decomposition is judged to be successful. Since two resolved signals are in opposite phase, the first arrival with positive first motion is taken to be the direct P-phase and the second the pP-phase. The final decomposition is expressed similarly to that for the event EKZ/333/06N as follows:

$$x(n) = s_p(n) + s_{pP}(n - \underset{\sim}{n}_o). \tag{III-4}$$

The resolved delay time, $\underset{\sim}{n}_o$, for this subarray is found to be 0.5 second.

Since the second resolved arrivals from the first path of cepstrum analysis have been determined to be the reduced mixed signals, the second path of cepstrum analysis is applied to them. Cepstra of these signals are also given in Figures III-12 through III-20, following those displays of results for the first path of cepstrum analysis. Except for the subarrays 13 and 18, the application of the shortpass filter at n = 5, where the first suspicious cepstral peak appears, successfully decomposes these reduced mixed signals into two single arrivals as shown in Figures III-12 through III-20. Thus, the second path of cepstrum analysis yields:

$$\underset{\sim}{x}_1(n) = \underset{\sim}{s}_2(n) + \underset{\sim}{s}_3(n - \underset{\sim}{n}_1), \tag{III-5}$$

where the resolved delay time, $\underset{\sim}{n}_1$, is found to be 0.5 second. The successful decomposition, given by equation (III-5), obtained by the second path of cepstrum analysis implies that the decomposition expressed in equation (III-3) is also successful. The final decomposition of x(n) can be obtained by substituting equation (III-5) into equation (III-3); i.e.,

$$x(n) = \underset{\sim}{s}_1(n) + \underset{\sim}{s}_2(n - \underset{\sim}{n}_o) + \underset{\sim}{s}_3(n - \underset{\sim}{n}_o - \underset{\sim}{n}_1). \tag{III-6}$$

When waveforms of $\underset{\sim}{s}_1$ and $\underset{\sim}{s}_2$ are examined, they are found to be similar and of opposite phase. Hence, we assign $\underset{\sim}{s}_1$ with positive first motion to be the direct P-phase and $\underset{\sim}{s}_2$ to be the pP-phase. Consequently, in Figures III-12 through III-20, equation (III-6) is written in the following form:

$$x(n) = s_{1P}(n) + s_{1pP}(n - \underset{\sim}{n}_o) + \underset{\sim}{s}_3(n - \underset{\sim}{n}_2), \tag{III-7}$$

where $\underset{\sim}{n}_2 = \underset{\sim}{n}_o + \underset{\sim}{n}_1$. For subarrays 13 and 18, although the second path of cepstrum analysis has failed, comparison of their first cepstrum-analyzed results with those having the successful cepstrum analysis in the second path leads to the conclusion that the decomposition given in equation (III-3) for these two subarrays probably is realistic.

As those observed in the event EKZ/333/06N, again, 30% variation (0.86 to 1.3) in the peak-to-peak amplitude ratio of s_{1pP} to s_{1P} is observed among these subarray signals. The amplitude ratio of $\underset{\sim}{s}_3$ to s_{1P} ranges from 1.0 to 2.3. The amplitude (peak) variation among the resolved s_{1P}'s is 3.5 to 1.1, in the same order as that for the original subarray signals. The similarity coefficient of s_{1P} and s_{1pP} is reasonably good, varying from 0.8 to 0.98.

For this event, a common result is obtained for eight out of nine subarray signals being analyzed. This common result is that the teleseismic short period P-waves of this event consist of a direct P-phase with its associated pP-phase delayed by 0.4 second and the other P-phase delayed by 0.9 second. For subarray 22, which gives only two single arrivals instead of three common to all other subarrays, the resolved P-pP delay time of 0.5 second agrees well with that of 0.4 second obtained from the other subarrays. Although the subarray 22 and the rest of the subarrays result in the different numbers of single arrivals, both cepstrum decompositions represented by equation (III-4) for the subarray 22 and equation(III-7) for the remaining are believed to be equally reliable based on the following reasoning: First, the same criteria for judging the cepstrum-analyzed results have been followed. Second, the amplitude spectra shown in Figure III-21 seems to support this viewpoint.

In Figure III-21, four amplitude spectra are presented: the subarray signals 22 and 11, the typical subarray signal of the event EKZ/333/06N, and a synthetically mixed signal consisting of two identical single P-phases, as follows:

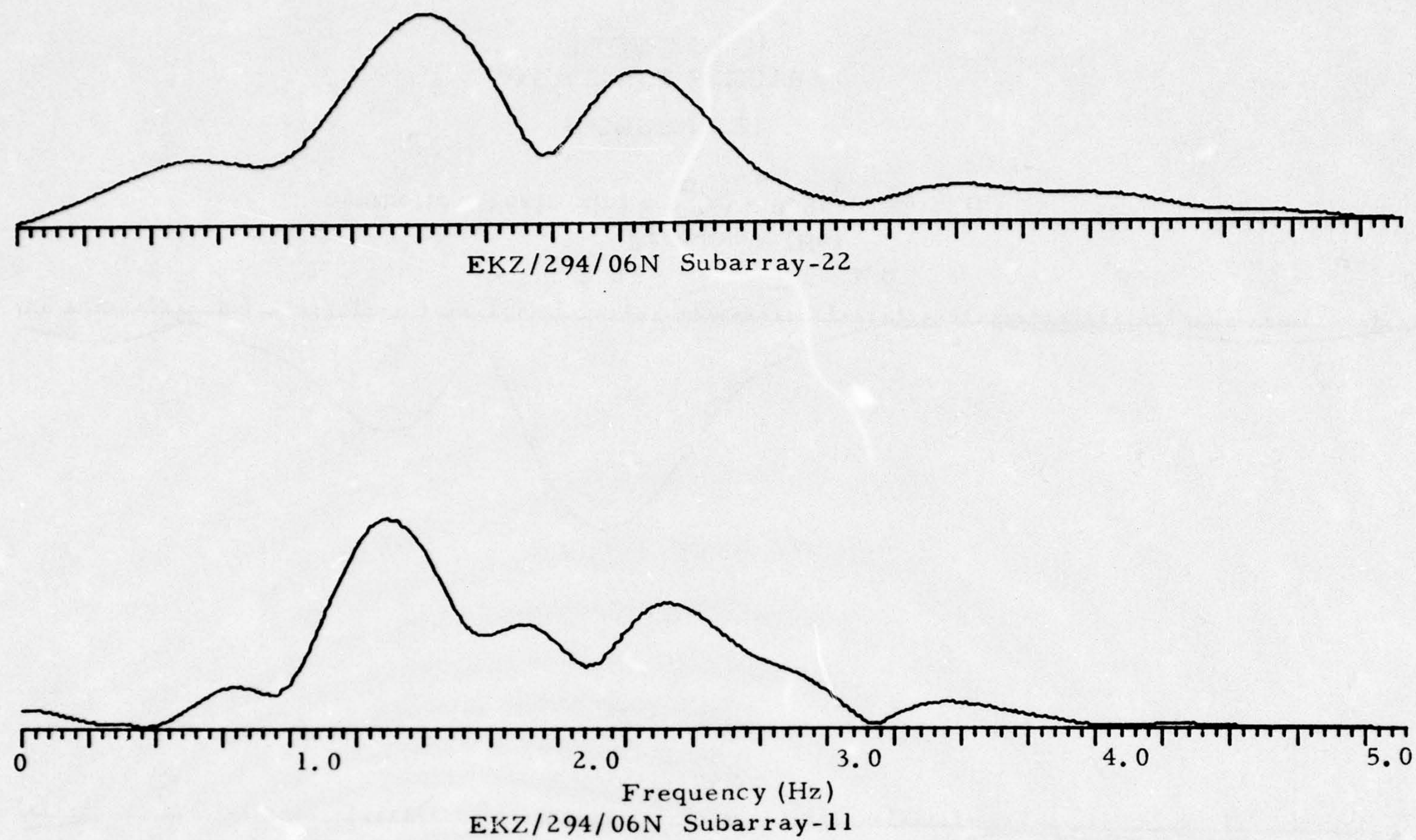
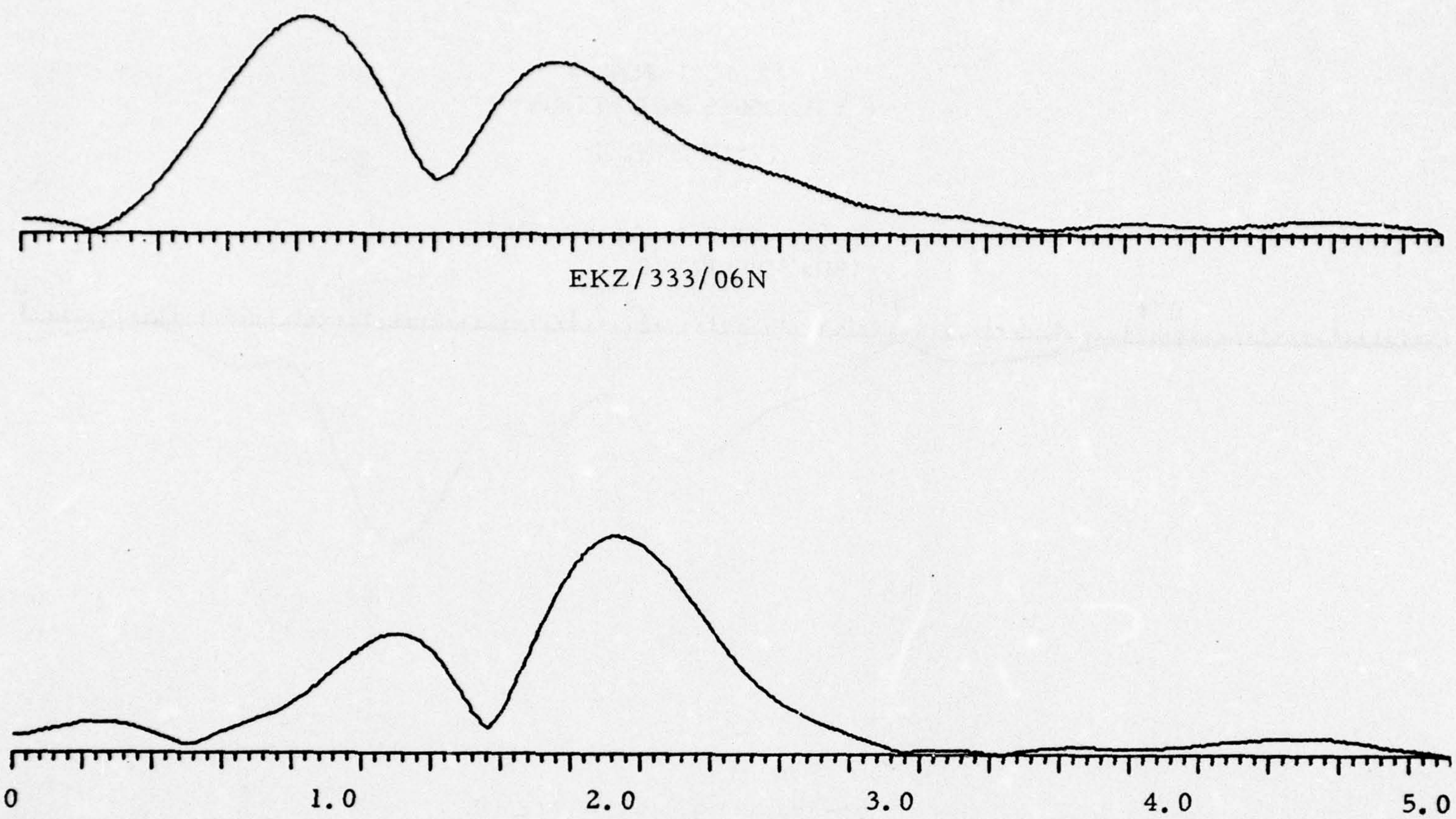


FIGURE III-21

AMPLITUDE SPECTRA
(PAGE 1 OF 2)



Synthetic Signal: $x(n) = s_p(n) - 0.9 s_p(n-6) + \ (n)$

FIGURE III-21

AMPLITUDE SPECTRA
(PAGE 2 OF 2)

$$x(n) = s_P(n) - 0.9\, s_P(n - n_o) + \epsilon(n), \qquad \text{(III-8)}$$

where $s_P(n)$ is a single P-phase of some EKZ event, n_o is 0.6 second, and $\epsilon(n)$ is the real seismic noise associated with $s_P(n)$. Here, the selected noise level yields x(n) with a SNR of 18 dB compared to those of the subarray signals. It is quite clear that the amplitude spectrum of the subarray 22 is very similar to that of the synthetically mixed signal and the subarray signal for the event EKZ/333/06N, both consisting of a direct P-phase and a delayed pP-phase; while the amplitude spectrum of the subarray 11 shows more complicated modulation, suggesting that the signal possibly consists of more than two single arrivals.

D. CONCLUSIONS

Analysis of two EKZ events has yielded fairly consistent results among the nine different NORSAR subarray signals being used. For the event EKZ/333/06N, results obtained from all nine subarray signals indicate that it is a single event and its teleseismic short period signal consists of two single phases: a direct P-phase and a surface reflected pP-phase delayed by about 0.6 second. For the event EKZ/294/06N, a possible double event has been suggested by 90% of the results, with 80% of them indicating that its teleseismic short period signal consists of a direct P-phase with its associated pP-phase delayed by 0.4 second and another P-phase delayed by 0.9 second.

Although the largest separation between any two NORSAR short period subarrays is only about one degree, a considerable signal variation, both amplitude and waveform, has been observed among the nine subarray signals being analyzed. This signal variation is also observed among the cepstrum-resolved signals of these subarray signals. These results lead to the following conclusions:

- Cepstrum-resolved delay times, especially the P-pP delay time, can be expected to be quite reliable, even when only one recorded signal is used. However, the amplitude ratios among the resolved signals vary quite noticeably among several different recorded signals being analyzed. This seems to imply that the amplitudes and the waveforms of the signals are very easily influenced by the different travel paths and local geology, while the relative delay times among them are not so influenced.

- The idea of cepstrum analysis of an event using signals recorded at several different stations is good in the sense that several independent estimates for the same event can be obtained, and results common to these estimates can then be taken with more confidence as the source effect. While the obtaining of several independent estimates gives no real problem, except taking more of the analyst's time to get a given event analyzed, the assigning of the common results to the true source effect creates some question, the answer to which sometimes depends heavily on the individual analyst's opinion. For example, for the event EKZ/333/06N, there is no question in deciding what is the source effect, because the results are common to all nine subarray signals. However, for the event EKZ/294/06N, we have chosen the results common to the majority of the subarray signals to be the source effect.

SECTION IV
BEAMFORMING IN CEPSTRUM TIME DOMAIN

A. INTRODUCTION

In the last report (Sun, 1975), the following conclusions were found:

- For the synthetically mixed signal consisting of identical P-phase and pP-phase, the lower bound of the signal-to-noise ratio (SNR) for the unambiguous detection of the cepstral peaks due to the P-pP delay time is about 18 dB; and
- For non-identical yet similar P-phase and pP-phase which usually is the case in a real seismic signal, no nice periodic appearances of these cepstral peaks can be expected. However, there always exists a suspicious cepstral peak, although not as sharp as theoretically predicted, at the right time equal to the true P-pP delay time to help out the detection.

Thus, in both cases, there exists a need to improve the complex cepstrum technique for obtaining better detection of those cepstral peaks for SNR below 18 dB, in the first case, and for providing easier identification of the first suspicious cepstral peak, in the second case. It is quite obvious, then, that the required improvement is to enhance the amplitudes of the desired cepstral peaks relative to the cepstra surrounding them. For this purpose, the application of the conventional time-domain beamforming technique in the cepstrum time domain appears to be appropriate. Without changing the basic formulation of the complex cepstrum technique, the beamforming in the cepstrum time domain (BFCEP) is expected to accomplish its goal by

performing either straight or weighted summations of the cepstrum of all pertinent signals. Aside from the above-mentioned purpose, the BFCEP can also be expected to solve the purpose of reducing those cepstral peaks which are due to the multiple arrivals not originating at the source region.

In this section, the BFCEP will be applied to several different groups of synthetic signals which are meant to simulate some real situations. In some cases, the effect of the BFCEP can be easily understood from their mathematical expressions. However, since this is not possible in all situations, both mathematical expressions and the experimental results of the simulation runs will be given here.

B. PREPARATION OF SYNTHETIC SIGNALS

Four groups of synthetically mixed signals are constructed and will be used for the simulation runs in the next subsection to demonstrate the effectiveness of the BFCEP in overcoming those undesired factors which obscure the detection of the cepstral peaks due to the P-pP delay time. The undesired factors which will be considered here are: the noise, the multiple arrivals from the local scattering, and the dissimilarity of the direct P-phase and the surface reflected pP-phase. In the following paragraphs, the synthetic signals will be formed to include these factors, one at a time. The class of signals which will be used here is the teleseismic short period P-waves (with sampling rate of 10 samples per second) of the presumed underground explosion in eastern Kajakh (EKZ) recorded at NORSAR.

1. Noise

The first group of synthetic signals is constructed as follows:

$$x_i(n) = s(n) - a\, s(n - n_o) + \epsilon_i(n) \qquad i = 1, N. \qquad \text{(IV-1)}$$

where $x_i(n)$, which consists of a P-phase $s(n)$, an ideal pP-phase - $as(n - n_o)$ delayed by n_o sampling units and the noise $\epsilon_i(n)$ in the i^{th} channel represents the signal recorded at the i^{th} channel for a given event. In equation (IV-1), we have assumed that the exact starting time of the signal for each channel is unmistakenly picked. In general, equation (IV-1) should be expressed in the following form:

$$x_i(n) = s(n - n_i) - as(n - n_i - n_o) + \epsilon_i(n) \qquad i = 1, N \qquad \text{(IV-2)}$$

where n_i accounts for the error being made in determining the exact starting time of the signal at the i^{th} channel. However, in the process of cepstrum analysis, the linear phase, which is produced by the time shift n_i in the time domain, is detected and removed. Thus, the complex cepstrum of $x_i(n)$ given by equation (IV-1) will be identical to that given by equation (IV-2). Hence, unlike the beamforming in the time domain where the exact time alignment among all channels is very critical, the error in picking the exact starting time of the signal for each channel will not affect the beamed cepstrum. Therefore, in this section, all synthetic signals will be given in the form of those in equation (IV-1).

In equation (IV-1), we have also assumed that signals of different channels are identical; i.e., $s(n)$ is used instead of $s_i(n)$. It is obvious that this assumption is not too realistic. In general, $x_i(n)$ should be expressed as follows:

$$x_i(n) = s_i(n) - as_i(n - n_o) + \epsilon_i(n) \qquad i = 1, N. \qquad \text{(IV-3)}$$

where s_i's are different among channels. However, in the simulation runs, two groups of synthetic signals, one formed according to equation (IV-1) and the other according to equation (IV-3), will both be used for the following reasons: Using $x_i(n)$ given by equation (IV-1), we can examine the sole

effect of noise on the beamed cepstrum. Moreover, we will be able to compare the results of both groups to see the effect of the signal dissimilarity among channels on the beamed cepstrum.

2. Multiple Arrivals

To see the effect of the BFCEP on multiple arrivals which are recording-station oriented, such as due to the local scattering and different travel paths, and not the source effect, the third group of synthetic signals are formed as follows:

$$x_i(n) = s(n) - a_1 s(n - n_1) + a_{2i} s(n - n_{2i}) \qquad i = 1, N, \qquad \text{(IV-4)}$$

where $x_i(n)$, $s(n)$, and $a_1 s(n - n_1)$ have the same meaning as before. The non-source-effect multiple arrivals are represented by the last term, $a_{2i} s(n - n_{2i})$. For simplicity in doing the analysis, yet without loss of generality, only one such arrival is included here. a_{2i} are different among channels and can be zero for some channels to reflect that some station-recorded signals are pure source effect.

3. Dissimilarity between the P-phase and the pP-phase

For the fourth group, the synthetic signals are formed as follows:

$$x_i(n) = s_{1i}(n) + s_{2i}(n - n_o) \qquad i = 1, N, \qquad \text{(IV-5)}$$

where $x_i(n)$ and $s_{1i}(n)$ have the same meaning as before, and $s_{2i}(n - n_o)$ represents the pP-phase which is not identical to the P-phase as expected in the real world.

C. RESULTS

In this subsection, for each group of synthetic signals some theoretical consideration on the BFCEP will be given first and then the experimental results from the simulation runs. In the following derivations, without loss of generality, the scale constants a, a_1, and a_{2i} involved in the synthetic signals will be taken to be positive and less than one (since in the cepstrum analysis, they can always be made to be less than one by proper weighting).

1. Noise

The complex cepstrum of $x_i(n)$ given by equation (IV-1) can be shown to be:

$$\hat{x}_i(n) = \hat{s}(n) - \sum_k \frac{a^k}{k} \delta(n - kn_o)$$

$$+ \text{ z-transform}^{-1} \left[\ell n \left(1 + \frac{E_i(z)/S(z)}{1 - az^{-n_o}} \right) \right]$$

$$i = 1, N, \qquad \text{(IV-6)}$$

where $\hat{x}_i(n)$ and $\hat{s}(n)$ are the complex cepstra of $x_i(n)$ and s(n) respectively; $E_i(z)$ and S(z) are the z-transforms of $\epsilon_i(n)$ and s(n), respectively. δ(n) is the Dirac delta function, and z-transform^{-1} stands for the inverse z-transform. The second term in equation (IV-6) provides the detection of the cepstral peaks due to the P-pP delay times. In general, as long as ϵ_i's are not identical and not perfectly correlated, the BFCEP should be able to increase the amplitude of these cepstral peaks relative to the surrounding cepstra which is represented by the last term in equation (IV-6). The beamed cepstrum, $\hat{x}_B(n)$, is obtained by summing up $\hat{x}_i(n)$ across all channels; i.e.,

$$\hat{x}_B(n) = \frac{1}{\sum_{i=1}^{N} w_i} \sum_{i=1}^{N} w_i \hat{x}_i(n), \tag{IV-7}$$

where w_i is a weighting constant for the i^{th} channel (for straight sum, $w_i = w_j$).

With some manipulation, it can be shown that:

$$\hat{x}_B(n) = \hat{s}(n) - \sum_k \frac{a^k}{k} \delta(n - kn_o)$$

$$+ \text{ z-transform}^{-1} \left\{ \frac{1}{\sum_{i=1}^{N} w_i} \ell n \left[\prod_{i=1}^{N} \left(1 + \frac{E_i(z)/S(z)}{1 + az^{-n_o}} \right)^{w_i} \right] \right\}. \tag{IV-8}$$

It is noticed that for this group of synthetic signals the only difference between the beamed cepstrum and the cepstrum of the individual channel is the last term in the corresponding equations. Hence, in order to determine mathematically whether the BFCEP has improved the detection of the cepstral peaks due to the P-pP delay time, we have to make a comparison of those two terms. It is clear that, quantitatively, the comparison is difficult, if not impossible. However, qualitatively, as discussed earlier, we can expect that the cepstral level of the last term in equation (IV-8) in general will be less than that in equation (IV-6). The following results of the simulation runs on this group will help in visualizing this comparison.

Figure IV-1 presents the cepstrum of five individual channels and the beamed cepstrum (straight sum) of these channels for the signal-to-noise ratio (SNR) of 18 dB and the P-pP delay time of 0.5 second (i.e., $n_o = 5$). Similar results are also given in Figures IV-2 and IV-3 for SNR = 12dB and

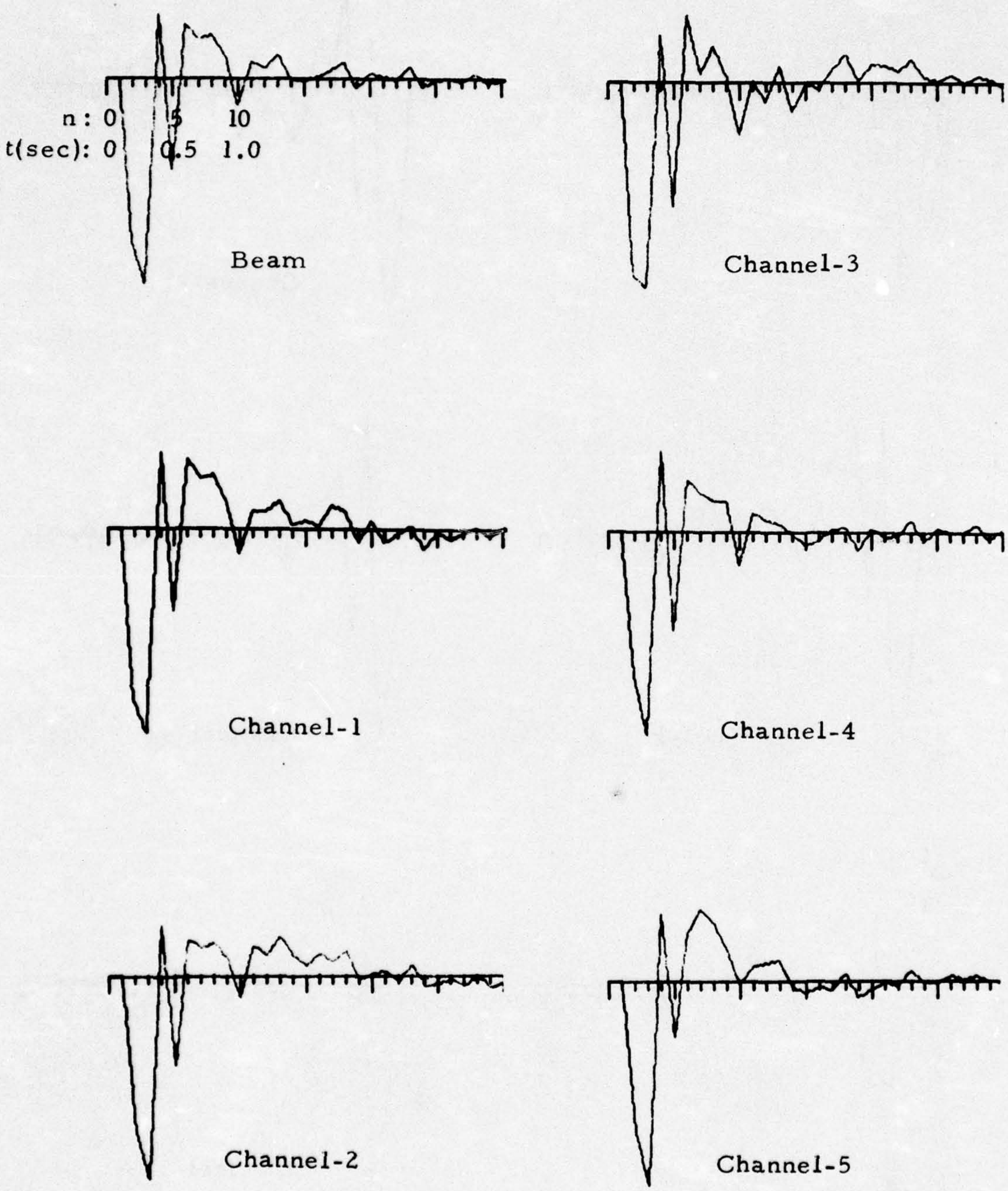


FIGURE IV-1

CEPSTRA OF BEAM AND INDIVIDUAL CHANNELS: SNR=18 dB

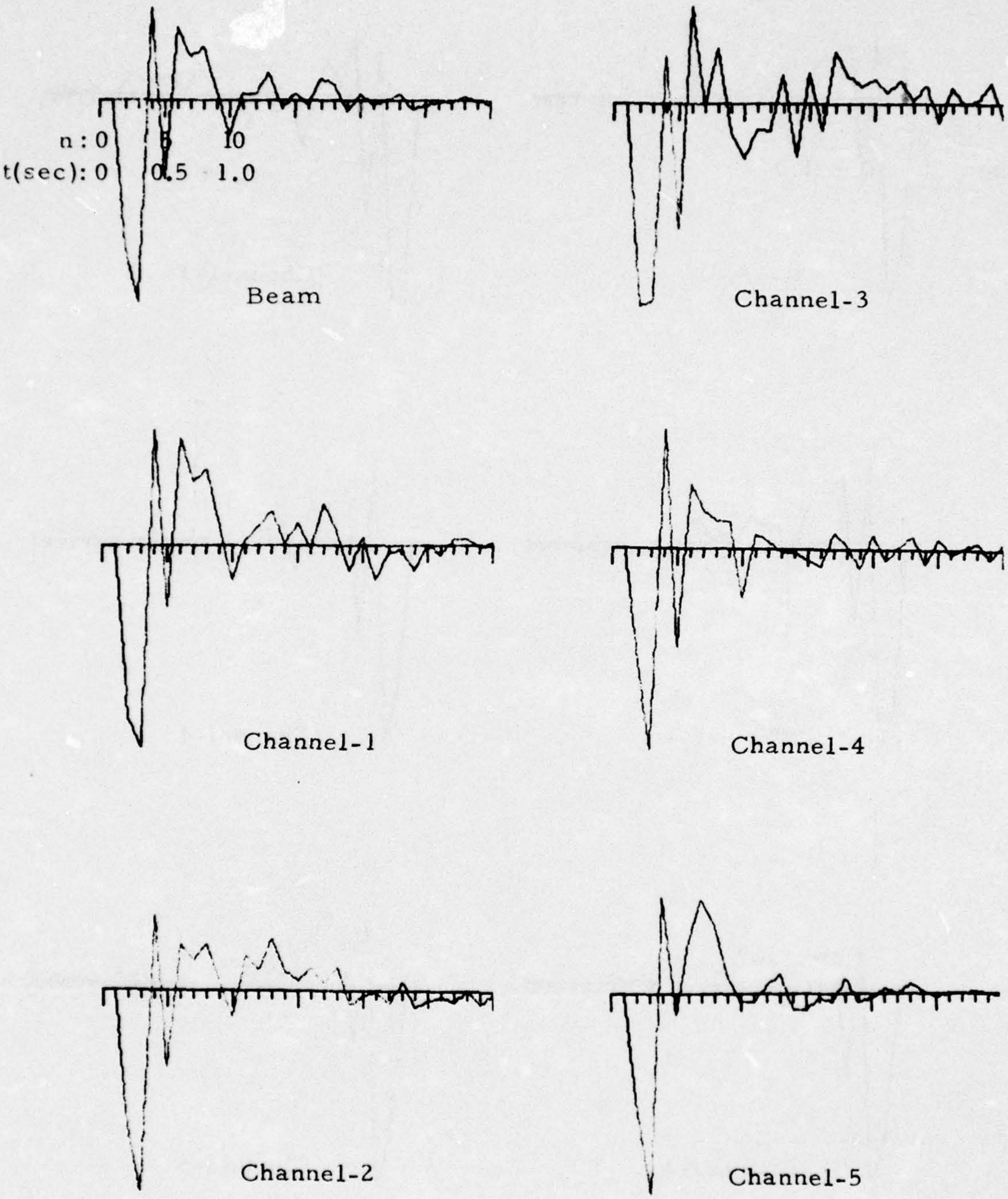


FIGURE IV-2

CEPSTRA OF BEAM AND INDIVIDUAL CHANNELS: SNR=12 dB

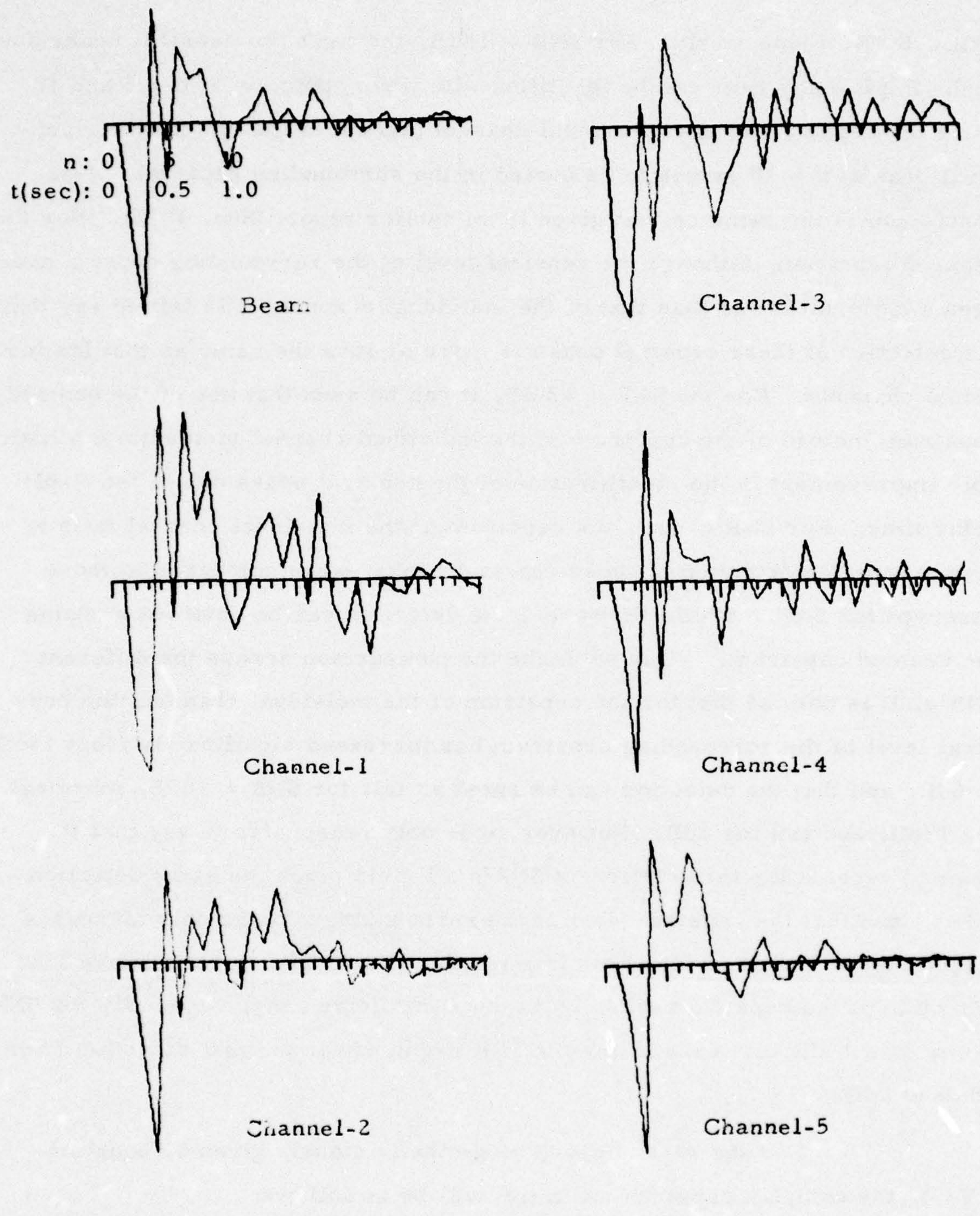


FIGURE IV-3

CEPSTRA OF BEAM AND INDIVIDUAL CHANNELS: SNR=6 dB

SNR = 6 dB, respectively. For SNR = 18dB, the first two cepstral peaks due to the P-pP delay time can be identified with little difficulty at n = 5 and 10, using the cepstrum of any individual channel (except in the 5th channel, cepstral peak at n = 10 seems to be buried in the surrounding cepstra). This conclusion is the same as that given in an earlier report (Sun, 1975). For the beamed cepstrum, although the cepstral level of the surrounding cepstra averages a little bit lower than that of the individual channel, it is fair to say that the detection of these cepstral peaks is more or less the same as that for individual channels. For the SNR = 12 dB, it can be seen that use of the beamed cepstrum instead of the cepstrum of the individual channel yields quite a noticeable improvement in the identification of the cepstral peaks due to the P-pP delay time. For SNR = 6dB, the cepstrum of the individual channel fails to give acceptable detection of these cepstral peaks, when compared to those observed for SNR = 18dB. However, the detection can be obtained by using the beamed cepstrum. When we make the comparison across the different SNR's, it is noticed that for the cepstrum of the individual channel, the cepstral level of the surrounding cepstrum has increased significantly from 18dB to 6dB, and that the detection can be rated as fair for SNR = 18dB, marginal for 12dB, and fail for 6dB. However, it is only reasonable to say that the beamed cepstra for three different SNR's all yield much the same detection -- fair -- and that the cepstral level of the surrounding cepstra only increases slightly from 18dB to 6dB. This implies that the BFCEP does improve the detection of the cepstral peaks due to the P-pP delay time, especially for SNR lower than 18dB; and does lower the SNR required for the fair detection from 18dB to 6dB.

For the second group of synthetic signals given by equation (IV-3), the complex cepstrum of $x_i(n)$ will be as follows:

$$\hat{x}_i(n) = \hat{s}_i(n) - \sum_k \frac{a^k}{k} \delta(n - kn_o)$$

$$+ \text{ z-transform}^{-1}\left[\ell n\left(1 + \frac{E_i(z)/S_i(z)}{1 - az^{-n_o}}\right)\right] \quad i = 1, N. \quad \text{(IV-9)}$$

The beamed cepstrum is:

$$\hat{x}_B(n) = \hat{s}_B(n) - \sum_k \frac{a^k}{k} \delta(n - kn_o)$$

$$+ \text{ z-transform}^{-1}\left\{\frac{1}{\sum_{i=1}^{N} w_i} \ell n\left[\prod_{i=1}^{N}\left(1 + \frac{E_i(z)/S_i(z)}{1 - az^{-n_o}}\right)^{w_i}\right]\right\} \text{(IV-10)}$$

where:

$$\hat{s}_B(n) = \frac{1}{\sum_{i=1}^{N} w_i}\left[\sum_{i=1}^{N} w_i \hat{s}_i(n)\right].$$

The difference between equations (IV-8) and (IV-10) is the first term in the equation. That is, when the direct P-phase is non-identical among channels, the beamed cepstrum of the P-phase is no longer the same as the cepstrum of the P-phase in the individual channel. Without any a priori knowledge about $\hat{s}_i(n)$, it is impossible to say whether $\hat{s}_i(n)$ or $\hat{s}_B(n)$ will produce more unfavorable influence on the detection of the cepstral peaks due to the P-pP delay time which is represented by the second term in the equation. However, based on the following reasoning, it is fair to say that $\hat{s}_B(n)$ and $\hat{s}_i(n)$ probably will behave in the same way. In general, $\hat{s}_i(n)$ can be considered to be of finite length; i.e., $\hat{s}_i(n) \approx 0$ for $n > M$ where M is a finite number (for EKZ events M is about 0.4~0.6 second) and so will be $\hat{s}_B(n)$. Also, the cepstral level of $\hat{s}_B(n)$ might be expected to be less than that of $\hat{s}_i(n)$ as long as s_i's

are non-identical and not perfectly correlated. Hence, for this group, the major factor in obscuring the detection will be the third term; i.e., noise in the equations (IV-9) and (IV-10) as that observed in the first group just discussed.

Figures IV-4 through IV-6 present the results for this group similar to those shown in Figures IV-1 through IV-3 of the first group. Here, the similarity coefficient of $s_i(n)$ and $s_j(n)$ ranges from 0.7 to 0.85. It can be seen that although the various cepstra of this group are quite different from those of the first group, conclusions concerning the detection of the cepstral peaks due to the P-pP delay remain more or less the same; namely, the beamed cepstrum has yielded better detection over the cepstrum of the individual channel, and the requirement of SNR for fair detection is reduced from 18dB to 6dB through the BFCEP.

2. Multiple Arrivals

The complex cepstrum of $x_i(n)$ given in equation (IV-4) can be shown to be:

$$\hat{x}_i(n) = \hat{s}(n) - \sum_k \frac{a_1^k}{k} \delta(n - kn_1)$$

$$+ \sum_k \frac{(-1)^{k+1}}{k} a_{2i}^k \delta(n - kn_{2i})$$

$$+ \sum_k (-1)^{k+1} \frac{1}{k} \sum_{r=1}^{k-1} \binom{k}{r} (-a_1)^{k-r} a_{2i}^r \delta\left[n - kn_1 + r(n_1 - n_{2i})\right]$$

$$i = 1, N. \qquad \text{(IV-11)}$$

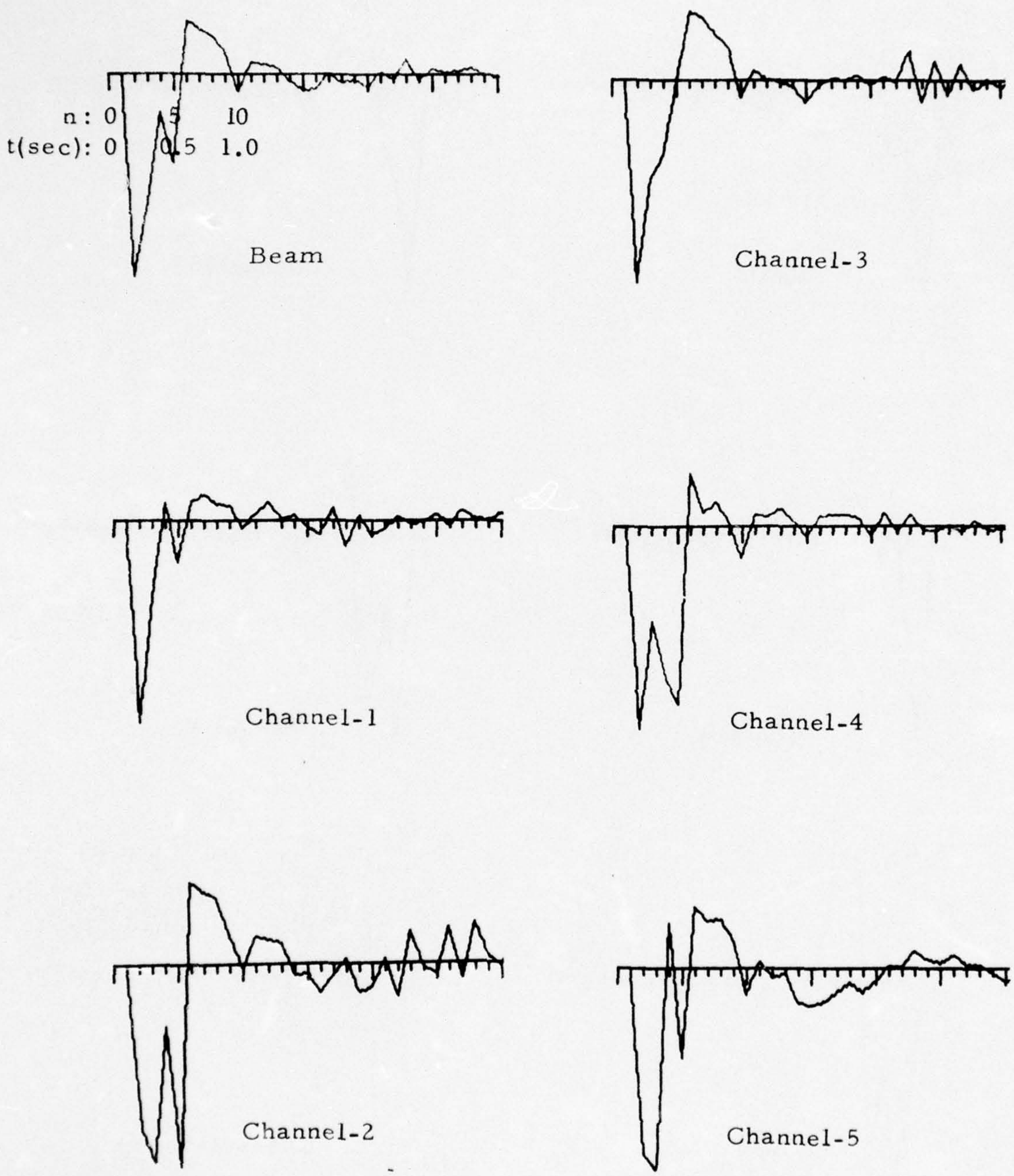


FIGURE IV-4

CEPSTRA OF BEAM AND INDIVIDUAL CHANNELS: SNR=18 dB

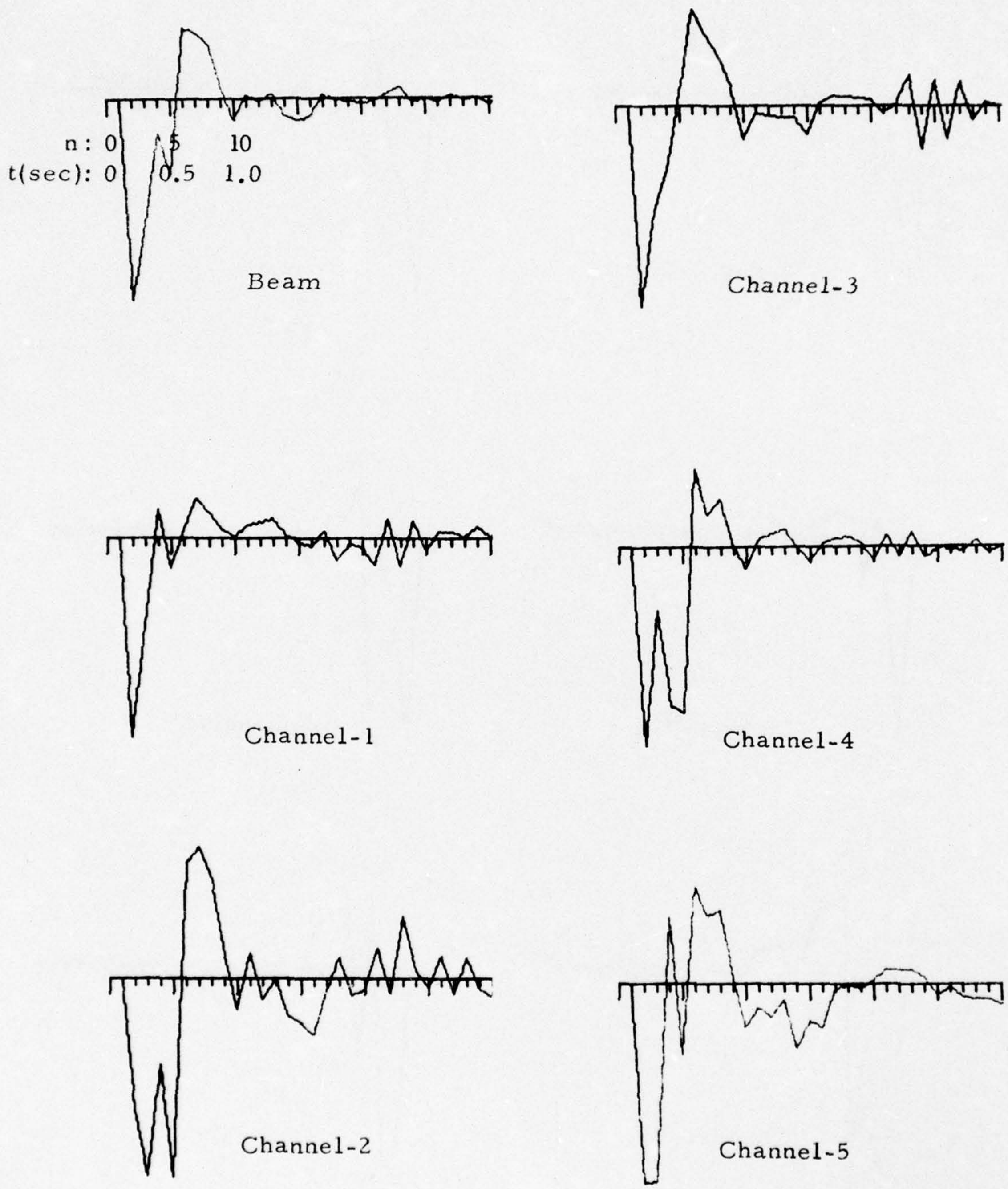


FIGURE IV-5

CEPSTRA OF BEAM AND INDIVIDUAL CHANNELS: SNR=12 dB

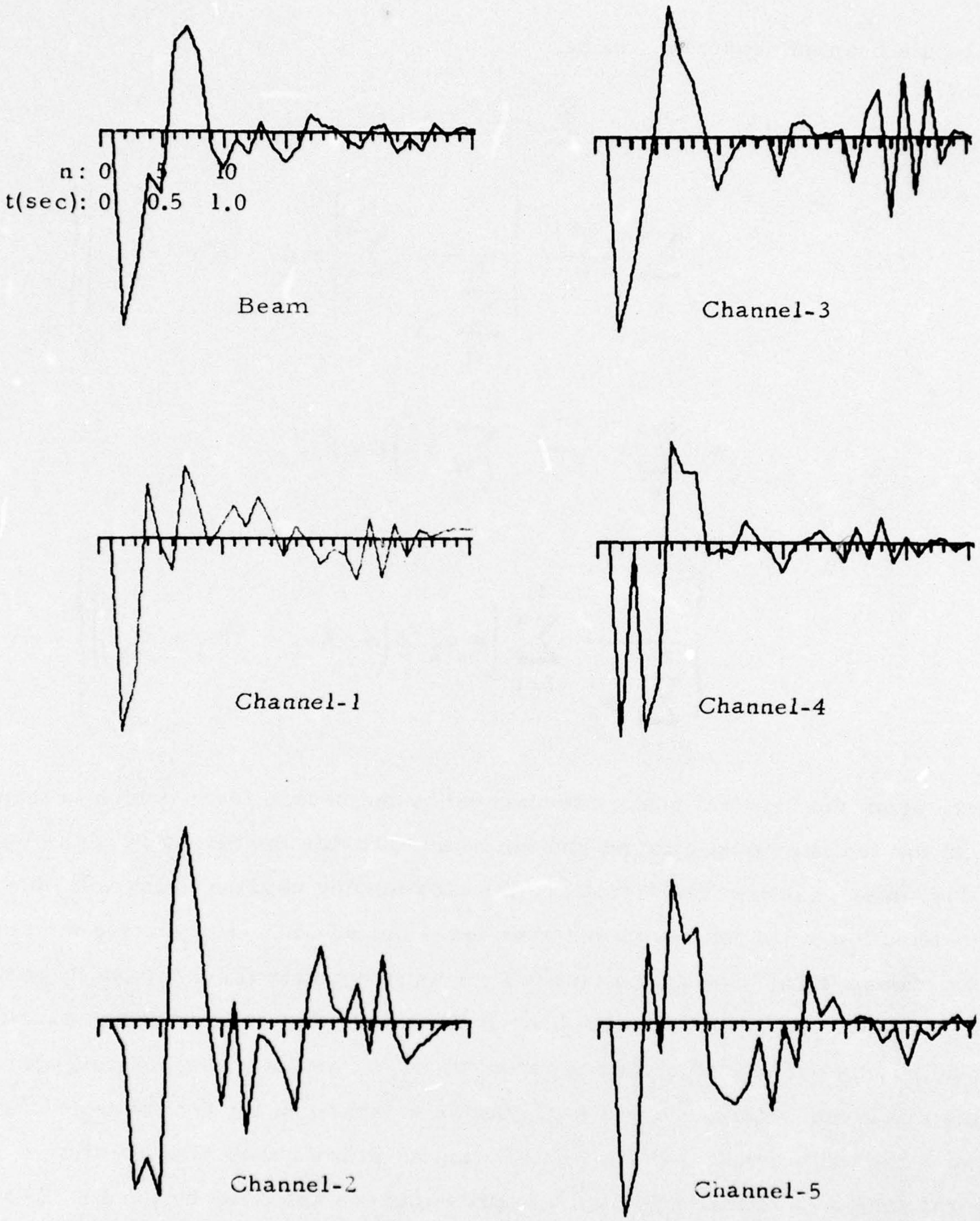


FIGURE IV-6

CEPSTRA OF BEAM AND INDIVIDUAL CHANNELS: SNR=6 dB

Then the beamed cepstrum will be:

$$\hat{x}_B(n) = \hat{s}(n) - \sum_k \frac{a_1^k}{k} \delta(n - kn_1)$$

$$+ \sum_k \frac{(-1)^{k+1}}{k} \left\{ \frac{1}{\sum_{i=1}^{N} w_i} \sum_{i=1}^{N} \left[w_i a_{2i}^k \delta(n - kn_{2i}) \right] \right\}$$

$$+ \sum_k \frac{(-1)^{k+1}}{k} \sum_{r=1}^{k-1} \binom{k}{r} (-a_i)^{k-r}$$

$$\left\{ \frac{1}{\sum_{i=1}^{N} w_i} \sum_{i=1}^{N} \left[w_i a_{2i}^r \delta\left(n - kn_1 + r(n_1 - n_{2i})\right) \right] \right\} . \quad \text{(IV-12)}$$

Here again the cepstral peaks represented by the second term, which is identical for the individual channel and the beam, provide the detection of the P-pP delay time. The last two terms are the surrounding cepstra which will obscure the detection. Therefore, in order to see if the BFCEP will improve the detection, the cepstral level of the last two terms in equation (IV-12) have to be compared with those in equation (IV-11). It is obvious that comparison is possible only if some predefined relations for w_i's, a_{2i}'s, and n_{2i}'s among all channels are given. Here, we will perform the comparison for two extreme cases: the worst and the best that the BFCEP can do in improving the detection. The worst case will be that there is no improvement in detection by the BFCEP. This will take place when $a_{2i} = a_{2j}$ and $n_{2i} = n_{2j}$ among all channels, and when $\hat{x}_B = \hat{x}_i$. The other extreme will occur when $a_{2i} \neq a_{2j}$ and $n_{2i} \neq n_{2j}$ for all i and j, except i = j. Then, the cepstral level of the last two terms

in the beamed cepstrum will be $\frac{1}{N}$ times of that in the cepstrum of the individual channel. This reduction in the cepstral level of the surrounding cepstra is the best that the BFCEP can provide. When the worst case occurs, the second P-phase arrived (i.e., $a_{2i}s_2(n - n_{2i})$ in equation (IV-4)) more likely is due to the source effect instead of the station-oriented phenomena as being assumed here. Hence, if the multiple arrivals are truly not the source effect, the BFCEP should be able to improve, to some degree, the detection of the cepstral peaks due to the P-pP delay time. Since the effect of the BFCEP for this case can be explicitly seen from the pertinent mathematical expressions, the results of the following simulation runs are just to serve the purpose of visual demonstration.

Two simulation runs have been made. Five channels are used. In both runs, we have assumed that channels 1 and 2 have no record P-phase arrival; i.e., $a_{21} = a_{22} = 0$, and the second P-phase arrivals in channels 3, 4, and 5 are delayed by 0.8, 0.9, and 1.0 second, respectively. The P-pP delay time is 0.5 second in the first run and 0.6 second in the second run. The choice of these values is quite arbitrary. Figure IV-7 presents the beamed cepstrum and the cepstrum of the individual channel for the first run. In both beamed and individual cepstra, the cepstral peaks due to the P-pP delay time appear at $n = 5k$, $k = 1, 2, \ldots$ and the cepstra level of these peaks is about the same. However, comparing the beamed cepstrum with the cepstra of channels 3, 4, and 5 where the second P-phase has been assumed to arrive, it is noticed that the cepstral level of the peaks due to the second P-phase arrival is much lower in the beamed cepstrum. This is just what should be expected as that described in the above theoretical discussion. Similar results for the second run are given in Figure IV-8.

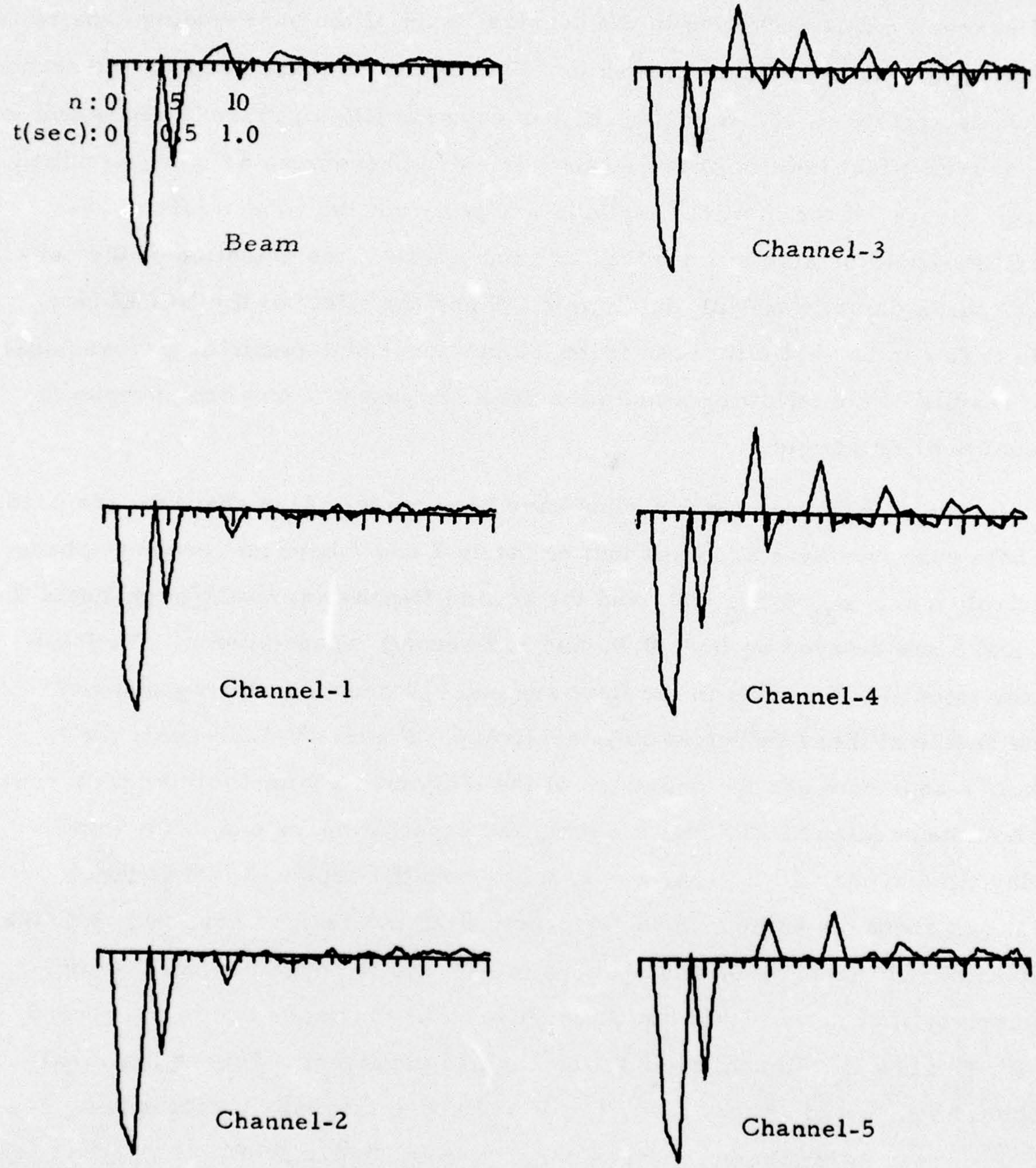


FIGURE IV-7

CEPSTRA OF BEAM AND INDIVIDUAL CHANNELS: $n_o=5$

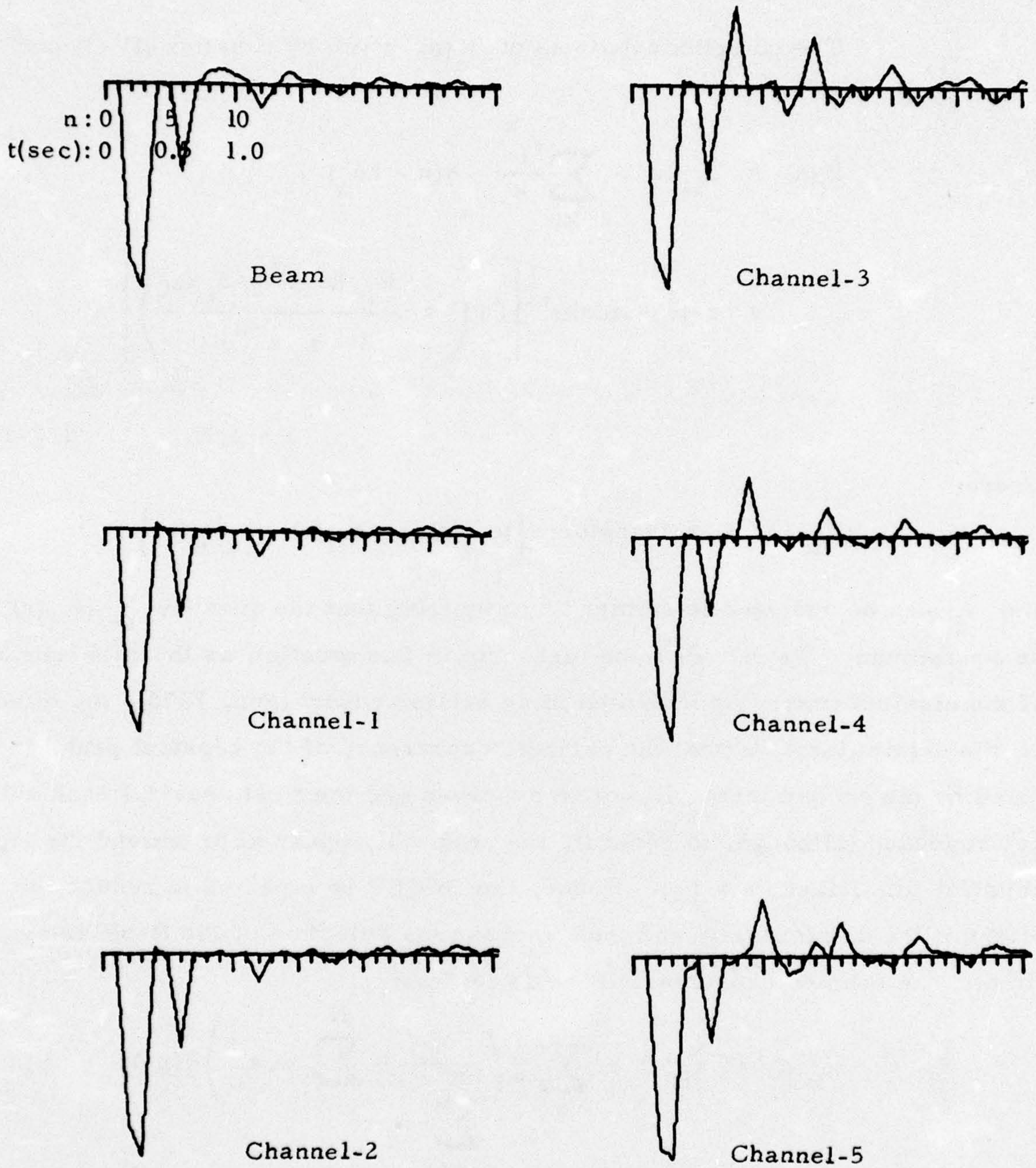


FIGURE IV-8

CEPSTRA OF BEAM AND INDIVIDUAL CHANNELS: $n_o = 6$

3. Dissimilarity Between the P-phase and the pP-phase

The complex cepstrum of $x_i(n)$ given by equation (IV-5) can be shown as follows:

$$\hat{x}_i(n) = \hat{s}_{1i}(n) - \sum_k \frac{a_i^k}{k} \delta(n - kn_o)$$

$$+ \text{z-transform}^{-1}\left[\ell n\left(1 + \frac{E_{id}(z)\, \delta^{-n_o}/S_{1i}(z)}{1 - a_i z^{-n_o}}\right)\right]$$

$$i = 1, N, \qquad \text{(IV-13)}$$

where:

$$E_{id}(z) = \text{z-transform}\left[(\epsilon_{id}(n) = s_{2i}(n) - a_i s_{1i}(n)\right]$$

and a_i can be uniquely determined by requiring that the quantity $\sum_n |\epsilon_{id}(n)|^2$ be a minimum. We can view the last term in this equation as the consequence of the dissimilarity. As indicated in an earlier report (Sun, 1975), the effect of this dissimilarity is that the periodic occurrence of the cepstral peaks indicated by the second term will not be observed and the first cepstral peak will be broadened (although, in general, the peak will appear at or around the right cepstral time, i.e., $n = n_o$). Hence, the BFCEP is expected to reduce the effect of the dissimilarity and thus improve the detection of the P-pP delay time. The beamed cepstrum will be as follows:

$$\hat{x}_B(n) = \hat{s}_B(n) - \sum_k \frac{1}{k}\left(\frac{1}{\sum_{i=1}^{N} w_i} \sum_{i=1}^{N} w_1 a_i^k\right)\delta(n-kn_o)$$

$$+ \text{z-transform}^{-1}\left\{\frac{1}{\sum_{i=1}^{N} w_i}\, \ell n\left[\prod_{i=1}^{N}\left(1+\frac{E_{id}(z)\, \delta^{-n_o}/S_{1i}(z)}{1 + a_i z^{-n_o}}\right)^{w_i}\right]\right\}. \qquad \text{(IV-14)}$$

where:

$$\hat{s}_B(n) = \frac{1}{\sum_{i=1}^{N} w_i} \left[\sum_{i=1}^{N} w_i \hat{s}_{1i}(n) \right] .$$

In dealing with the noise, we have shown that the beamed cepstrum of the P-phase, i.e., $\hat{s}_B(n)$, will not affect the detection one way or the other. Therefore, the improvement in detection by the BFCEP, if any for this case, should be coming from the interaction of the last two terms in equation (IV-13). However, the mathematical expressions are too complicated to show the effect of this interaction, explicitly and analytically. Hence, the easier alternative to show the effect of the BFCEP for this case will be the numerical results of the following simulation runs.

Figures IV-9 and IV-10 display the beamed cepstrum and the cepstrum of the individual channel for the P-pP delay times (n_o) of 0.5 and 0.6 second, respectively. Here, seven channels are used with the similarity coefficient of $s_{1i}(n)$ and $s_{2i}(n)$ varying from 0.6 to 0.9. For the run with $n_o = 5$ sampling units it is noticed that the first suspicious cepstral peak appears at $n = 5$ to 7 (varying among channels), and there exists several equally suspicious peaks at some other cepstrum times. In the beamed cepstrum, however, the first cepstral peak occurs at $n = 5$ which corresponds to the right P-pP delay time and the level of the surrounding cepstrum is comparatively lower. For the run with $n_o = 6$ sampling units, although the first suspicious cepstral peak appears at the right P-pP delay time ($n = 6$) for all channels, this peak seems to be sharper in the beamed cepstrum. Again, in the beamed cepstrum, the level of the surrounding cepstrum is much lower. Thus, it is reasonable to conclude that the BFCEP does make the identification of the first suspicious cepstral peak easier and more accurate.

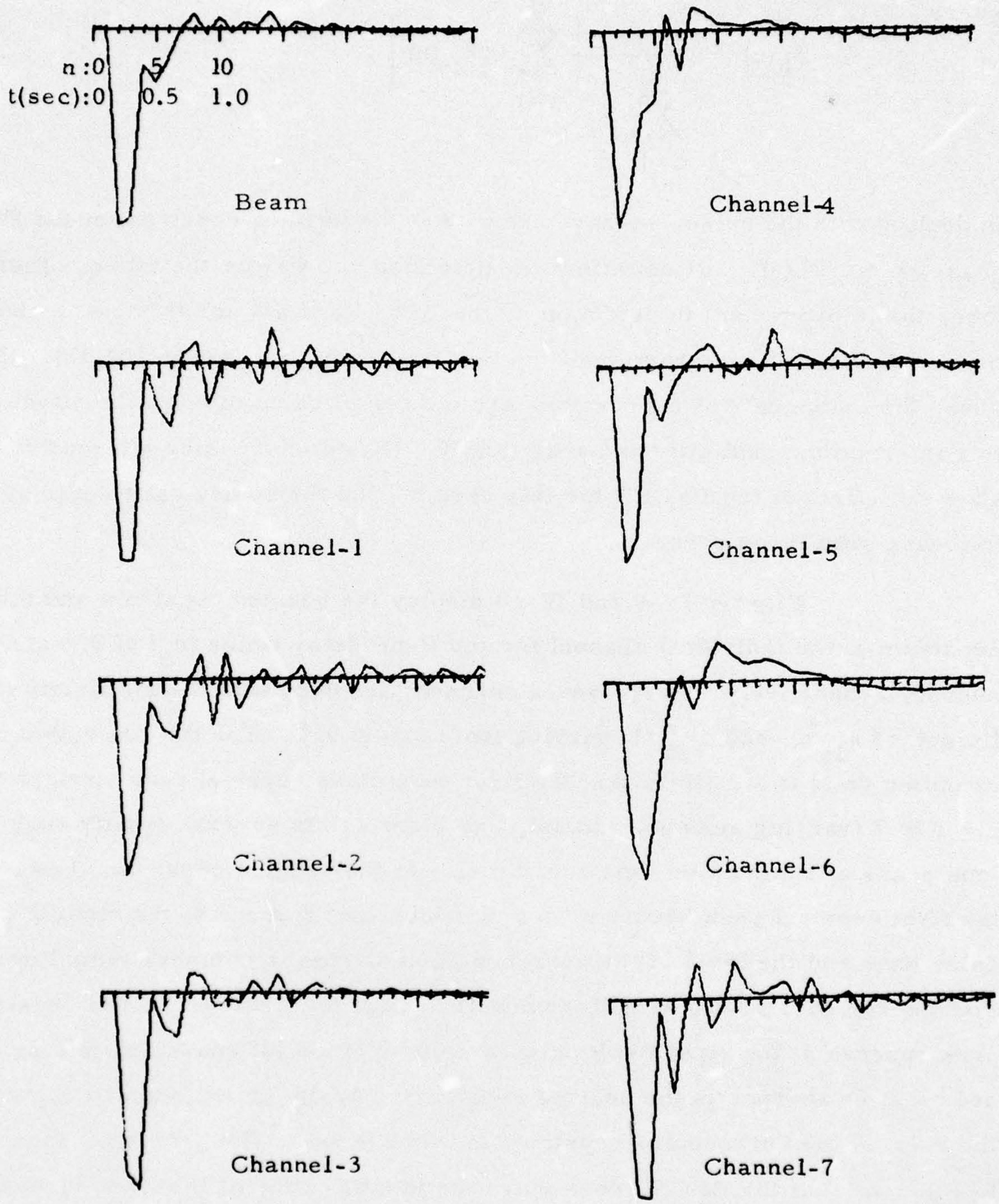


FIGURE IV-9

CEPSTRA OF BEAM AND INDIVIDUAL CHANNELS: $n_o = 5$

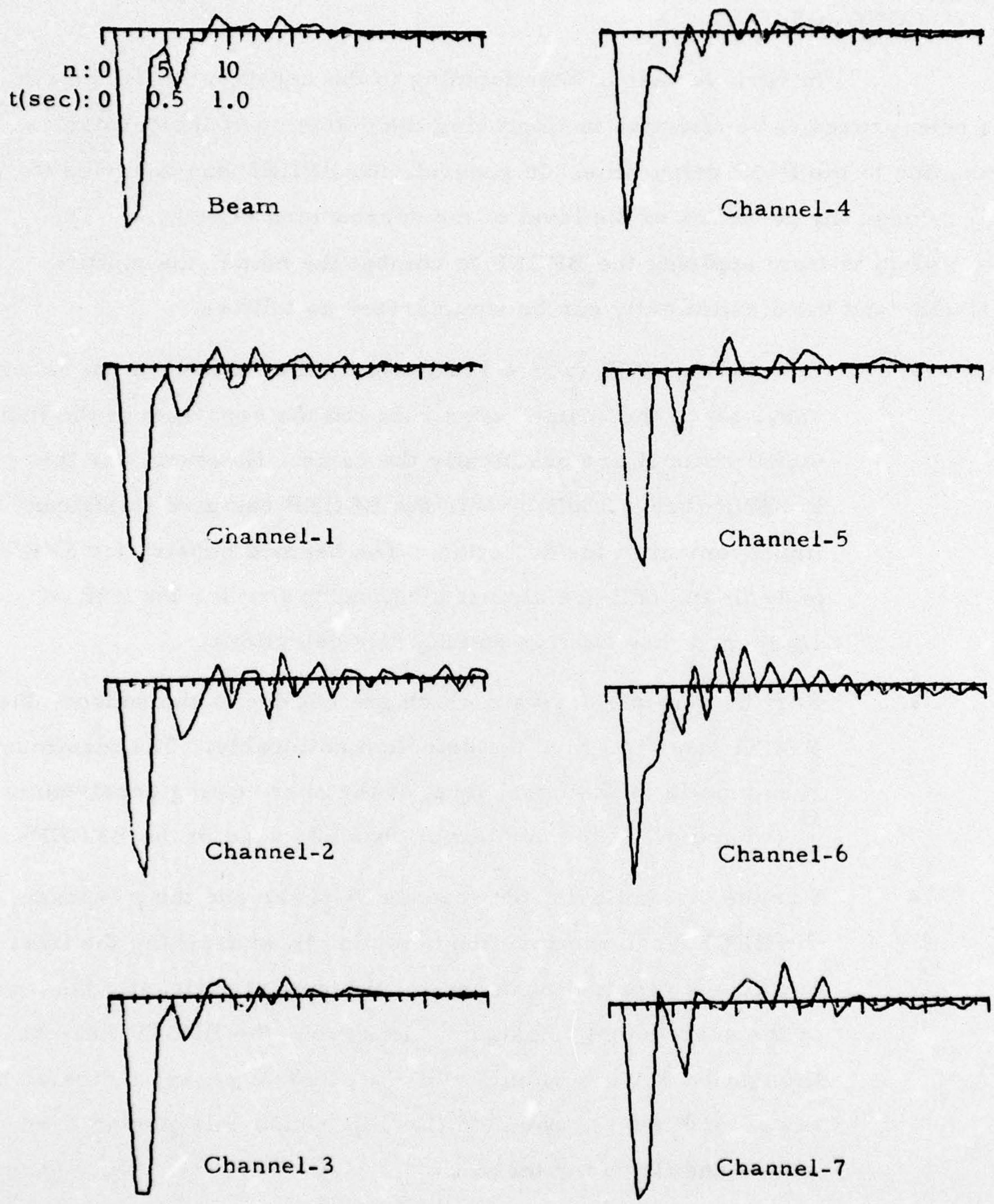


FIGURE IV-10

CEPSTRA OF BEAM AND INDIVIDUAL CHANNELS: $n_o = 6$

D. CONCLUSIONS

In various cases, beamforming in the cepstrum time domain has been proved to be effective in improving the detection of the cepstral peaks due to the P-pP delay time. In general, the BFCEP has achieved its goal through the reduction of the level of the surrounding cepstrum. The major results from applying the BFCEP to combat the noise, the multiple arrivals, and the dissimilarity can be summarized as follows:

- For the high SNR (above 18dB) event, the BFCEP is not necessary, since the beamed cepstrum and the cepstrum of the individual channel are practically the same. However, for the low SNR (below 18dB) event, the BFCEP can give significant improvement in the detection. The beamed cepstra for SNR's of 12dB and 6dB are almost identical to that for the SNR of 18dB, and they all give equally fair detections.
- For the multiple arrivals which are not due to the source, the BFCEP does improve the detection noticeably. The maximum reduction in the cepstral level of the surrounding cepstrum is $\frac{1}{N}$ (where N is the number of channels used in the BFCEP).
- For the dissimilarity between the P-phase and the pP-phase, the BFCEP can improve the detection by sharpening the first suspicious cepstral peak and by reducing significantly the level of the surrounding cepstrum. However, the BFCEP has not brought back the periodicity of the cepstral peaks, indicated by the second term in equation (IV-13), which will give an even easier and firmer detection.

In these simulation runs, the number of individual channels used is small: five for the first three groups and seven for the last. It is believed that the effect of the BFCEP will probably be more enhanced with a larger number of channels.

SECTION V
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Fifteen earthquakes with known PDE (Preliminary Determination of Epicenters) depths have been analyzed using teleseismic short-period P-waves recorded at NORSAR. Results from this analysis indicate that mis-decomposition by cepstrum analysis is unlikely, especially if the analyst follows the appropriate criteria closely.

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Also, two presumed underground explosions from eastern Kazakh (EKZ) have been analyzed using teleseismic short-period P-waves recorded at nine NORSAR subarrays with signal-to-noise ratio above 18 dB. Waveforms recorded at nine subarrays are quite dissimilar, especially for two subarrays on the west side of NORSAR. However, cepstrum-analyzed results are fairly consistent among them. The difference in the resolved delay times is one sampling unit (0.1 second) maximum. Although these subarrays are not located widely apart enough to be considered as separate stations at different azimuths, the good agreement of cepstrum-analyzed results among them is definitely a plus toward better recognition of the capability of the cepstrum analysis.

Finally, beamforming in cepstrum time domain (BFCEP) to enhance the detection of the cepstral peaks due to the multipath operator has been formulated and implemented. Several sets of synthetic signals, which simulate various cases of interest, have been used in the experiments. Preliminary results show that BFCEP in general does achieve its original purpose. Moreover, it appears that BFCEP can be expected to produce a better effect when signals used in BFCEP are less correlated. This, in the real world, may imply that BFCEP will work more effectively with the world-wide network data than with the single array data.